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Research and Development Report

Surface Ship Machinery—A Survey of Propulsion, Electrical, and Auxiliary System Development

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Propulsion, auxiliary and electric machinery targeted for future surface combatants is surveyed-overall system characteristics are treated to permit as broad as possible coverage of development activities. Prime movers in both propulsion and ship service sizes are discussed. All will demonstrate improved economy, especially at part power, and increased attention to thermal and acoustic signatures. Gas turbines will remain the uncontested source of propulsion power, but rotaries may join diesels and turbines in ship service application. Electric drives may be selected where machinery is widely separated or geometries are restrictive. Reversing motors or reversing gears will provide backing power without the inefficiencies of controllable pitch (CP) propellers. Transmission component improvements including surface hardened gears and composite shafts will increase power density. Shaftline elements compatible with contrarotating propellers may

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lead to significantly increased propulsive coefficients. Auxiliary machinery developments are driven by the need to improve performance in smaller, simpler packages with lower acquisition and operating costs. This encourages the development and adaption of new materials and design approaches such as composite structures, rotary screw pump and compressor arrangements, variable speed or geometry units, and molecular sieves and membrane separation for gas and fresh water production. The increasing demands for chilled water will be met by more compact and efficient refrigeration plants. Ventilation systems requirements will be expanded and integrated with the new demands of collective protection. The ship's service generation and distribution system will reflect the increasingly nonlinear character of electric loads. Developments will emphasize power quality and continuity in system arrangements which promote both survivability and energy efficiency. Propulsion derived ship's service, uninterruptible power at the system and component levels, and variable speed auxiliary motor drives reflect these thrusts.

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ABBREVIATIONS

ac	Alternating Current
APL	Allowance parts list
BC21	High temeprature gas turbine component coating developed in the early 1970's; Contains 21% Cr in a CoCrAly matrix
BESS	Battery energy storage system
CIP	Component Improvement Program
COGAS	Combined gas and steam
C/R	Contrarotating
CRP	Controllable reversible pitch
dc	Direct current
FP	Fixed pitch
GPD	Gallons per day
GRP	Glass reinforced plastic
GT	Gas turbine
HM&E	Hull, mechanical and electrical
hp	Horsepower
ICR	Intercooled and recuperated (or regenerated)
IEC	Integrated electronic control
JDTI	John Deere Technologies, Inc.
LM2500	Designation for marine gas turbine produced by General Electric
LTDR	Locked train double reduction
MTBO	Mean time between overhauls
MTBR	Mean time between removals
MTTR	Mean time to repair

ABBREVIATIONS (Continued)

PDSS	Propulsion derived ship service
RACER	Rankine cycle energy recovery system
RO	Reverse osmosis
RDT&E	Research, development, testing and evaluation
RRG	Reverse reduction gear
S/C	Superconducting
SFC	Specific fuel consumption
SSTG	Ship service turbine generator
SWATH	Small waterplane area twin hull
UPS	Uninterruptible power supplies
VAT	Variable area turbine
VCCP	Variable capacity centrifugal pump
VSCF	Variable speed constant frequency
VSV	Variable stator vanes

ABSTRACT

Propulsion, auxiliary and electric machinery targeted for future surface combatants is surveyed—overall system characteristics are treated to permit as broad as possible coverage of development activities. Prime movers in both propulsion and ship service sizes are discussed. All will demonstrate improved economy, especially at part power, and increased attention to thermal and acoustic signatures. Gas turbines will remain the uncontested source of propulsion power, but rotaries may join diesels and turbines in ship service application. Electric drives may be selected where machinery is widely separated or geometries are restrictive. Reversing motors or reversing gears will provide backing power without the inefficiencies of controllable pitch (CP) propellers. Transmission component improvements including surface hardened gears and composite shafts will increase power density. Shaftline elements compatible with contrarotating propellers may lead to significantly increased propulsive coefficients. Auxiliary machinery developments are driven by the need to improve performance in smaller, simpler packages with lower acquisition and operating costs. This encourages the development and adaption of new materials and design approaches such as composite structures, rotary screw pump and compressor arrangements, variable speed or geometry units, and molecular sieves and membrane separation for gas and fresh water production. The increasing demands for chilled water will be met by more compact and efficient refrigeration plants. Ventilation systems requirements will be expanded and integrated with the new demands of collective protection. The ship's service generation and distribution system will reflect the increasingly nonlinear character of electric loads. Developments will emphasize power quality and continuity in system arrangements which promote both survivability and energy efficiency. Propulsion derived ship's service, uninterruptible power at the system and component levels, and variable speed auxiliary motor drives reflect these thrusts.

INTRODUCTION

Machinery with its fuel is, by far, the largest contributor to the displacement of a modern surface combatant. To illustrate, Fig. 1 (from Levedahl[1]) shows that a SPRUANCE Class Destroyer carries four pounds of machinery and fuel for each pound of payload. Machinery has a similarly pervasive influence on ship acquisition and operating cost, arrangement, availability, crew size and skill level, detection signature, and virtually every other factor that affects mission capability. The developers and users of machinery systems, therefore, have an immense opportunity to favorably influence the performance and affordability of future ships by exploiting new technology and innovative design.

This paper "surveys" machinery components and systems now in the Navy research and development cycle. Hopefully, many who expect to be wrestling with

future tradeoffs between cost and capability, size and efficiency and the like might see some "solutions" coming along.

Future components and systems are classified and addressed under three major machinery headings: Auxiliary Machinery, Electric Plant, and Main Propulsion Systems. Each begins with an overview addressing technology and requirements thrusts appropriate to that machinery class. Specific developments follow. Wherever possible, "new" machinery is described in the context of functional requirements, current practice, the what, the why, and the how of new technology and designs, and the target dates when qualified hardware could be available. Areas are identified where favorable ship impacts might be expected. The magnitude of such benefits, of course, will depend on specific ship requirements and the mix of machinery systems selected—areas outside the scope of this paper.

AUXILIARY MACHINERY: OVERVIEW

MANY COMPONENTS

Auxiliary machinery developments are driven by the multiple needs to improve performance and operational availability, increase reliability and maintainability, reduce required manning and life cycle costs, and at the same time package the machinery in a smaller, lighter, and more accessible and repairable package.

Developments are initiated because of both "pushes" from promising technology and "pulls" from operational needs. When innovative new auxiliary machinery concepts are proposed by the Navy's in-house Research and Development Centers or industry, they are evaluated in the axiliary machinery exploratory development program.

The needs "pulls" are evolved by Chief of Naval Operations project directives, Naval Sea Systems Commands life-cycle or product line managers, Ship Acquisition Project Managers, Ship Life Cycle Managers, and in-service engineering agents based upon input they have received from the Fleet, casualty reports, Fleet material readiness reports, hull, mechanical, and electrical (HM&E) conferences, and shipboard in-service inspection reports.

Because of the multiplicity of goals, equipments, systems, and new technologies and the constraints of a tight budget, projects are given priorities based upon payoff, risk, timeliness, and cost.

Typically programs progress from an exploratory development feasibility demonstration to advanced development, which usually includes:

- A breadboard or engineering development model design, fabrication, and laboratory or shipboard evaluation.
- An advanced development model or prototype design and fabrication.
- A laboratory evaluation of a militarized prototype followed by a ship evaluation (SHIPEVAL), a technical evaluation (TECHEVAL), and an operational evaluation (OPEVAL).
- Approval for Full Production.

The Table 1 lists the auxiliary machinery developments described in this paper, the emerging technology used, and the gains anticipated from these developments.

Table 1. Emerging technologies.

System	Technology	Major Driver
LPAC/HPAC Compressors Air Conditioning Compressors Positive Displacement Pumps	Balanced Rotary Screw	Performance, Reliability, and Maintainability
Air Conditioning Systems	Advanced Heat Transfer Surfaces	Energy Efficiency, Size, and Weight
Centrifugal Pumps	Computer Developed Family, Composite Materials, Close Coupled Design	Logistics Burden, Performance, Reliability, and Maintainability
Fire Pumps	Variable Capacity Centrifugal Pump	Reliability, Maintainability, and Performance
Water Production	Reverse Osmosis Disinfection	Performance, Reliability, Maintainability, Size, Weight, and Cost
Potable Water Disinfection	Closed Cell Electrolytic Chlorine Generator	Performance, Reliability, Maintainability, and Cost
Nitrogen Generation	Molecular Sieves	Performance, Changing Requirements, Reliability, and Maintainability
Piping Systems Ventilation Systems	Composite Materials	Weight, Cost, and Performance

COMPRESSORS/POSITIVE DISPLACEMENT PUMPS

The Problem

High pressure air and refrigerant compressors have traditionally been reciprocating machines. The Navy has approximately 3,500 reciprocating air compressors of various sizes, pressures, and designs in the Fleet. Reciprocating multistage compressors are complex mechanisms composed of hundreds of parts; many of them move, impact, or wear. Most have oil-free air ends and have from two to six stages of compression. Each stage has its own piston, cylinder, rings, rod seals, valves, intercooler, separator, and drain system. Additionally, the pistons are driven

by a relatively complex slider crank mechanism with its crankshaft, connecting rods, crosshead and lubrication system.

Similarly, high pressure pumps can be of either the reciprocating or the rotary vane, gear, or screw type. As with compressors, the reciprocating piston or plunger pumps are complex, have many moving parts, experience valve and seal wear, and normally produce high structureborne and fluidborne noise levels. In addition, these pumps must operate at low speed because of suction head limitation. Vane pumps have close clearances and require rubbing seals. The vanes slide within radial slots in the rotor and are loaded against the housing end plates to prevent excessive leakage. Operating pressure is limited by radial thrust loads on the rotor bearings and vane bending stresses. Rotary gear pumps require close clearances between the gears and housing and must transmit power from the driver to the idler gear. Internal radial thrust loads generally limit the maximum pressure.

Rotary screw pumps are the most common positive displacement pumps in naval service. The two types used are the twin-screw pump (surface ship lube oil, fuel oil boost) and the triple-screw pump (surface ship fuel oil service and submarine lube oil and hydraulic systems). These pump designs have high stresses in the screws and rotors at high pressure, and have extensive rolling and rubbing contact area.

The Solution—Balanced Pressure Screw Machines

Rotary compressors offer the potential of significantly fewer parts and reduced complexity. In the late 1970's a new and unique low pressure rotary, water flooded, twin helical screw machine was developed and successfully evaluated. These machine compressors demonstrated substantial advantages in reliability, maintainability, size, weight, noise and vibration over similar service reciprocating compressors.

While suitable for low pressure service, the twin screw compressor concept cannot be easily extended to a high pressure design because of high rotor stresses. A state-of-the-art survey was done in 1977 to determine if any alternative rotary mechanisms could be developed for pressures to 3,000 psi. This study indicated that while no suitable oil-free, high-pressure rotary machine existed nor did any manufacturer plan to market any in the foreseeable future, a promising design conept existed. The Balanced Rotary Screw Machine, Fig. 2, invented by Zimmern, had many features which should offer significant advantages over any current designs:[2,3]

- Few moving parts—Three major moving parts, a main rotor and two gate rotors. No cylinders, valves, pistons, or impacting parts; all motion is rotary.
- Low mass of moving parts—low bearing and inertial loads.
- Balanced forces on main rotor—Diametrically opposed forces allow high pressures without major bending moments on main rotor.
- Rubbing forces not pressure dependent—Wear should not increase with pressure.
- Low operating temperatures—Fluid injection into the main rotor thread seals against leakage, lubricates the rotors, and absorbs the heat of compression.
- Fewer stages—Pressure ratios of ten are readily obtainable in one stage.
- Good volumetric and mechanical efficiencies.

NAVY PROGRAMS

Under the Navy exploratory and advanced development R&D programs the balanced rotary screw design concept is being exploited for the following applications:

- Air compressors
- Refrigerant compressors
- Positive displacement pumps

Technology issues include developing bearings and gate rotor materials and configurations which can operate in an oil-free, water lubricated or refrigerant lubricated environment. Designing main rotor and gate rotor configurations which can develop the required pressures with a minimum of wear and a high volumetric efficiency.

These studies have relied on extensive use of two and three dimensional computer modeling, numerically controlled tooling, and empirical tests which have been performed on a wide range and combination of planar and cylindrical main rotor and gate rotor configurations.

Air Compressors

The Zimmern commercial oil lubricated machine has been developed into a compressor for military application. It is water lubricated with a 200 scfm, 125 psi capacity. This unit has successfully completed laboratory endurance tests, shock tests, electromagnetic interference tests, and vibration tests, and is undergoing TECHEVAL (Fig. 3). OPEVAL is now underway.

The 3000 psi machine is still in the breadboard modeling stage. At low flow rates, laboratory prototypes have successfully generated a discharge pressure of 3,000 psi using a cylindrical main rotor and cylindrical gate configuration with 100 psi suction pressure (Fig. 4).

Refrigerant Compressors

These compressors are particularly attractive for advanced energy efficient air conditioning systems.[4,5] Single screw compressors can provide theoretical full load isentropic efficiencies of 75% compared to 64% and 67% for reciprocating and centrifugal units.

In addition to the reliability and performance features described previously, a balanced screw compressor would also allow the use of liquid refrigerant as the injection fluid, providing for the sealing of rotor threads, lubrication of bearings, and cooling of the compression process. This oil free feature eliminates large oil separators, strainers, filters, and pumps and substantially reduces compressor complexity.[6] The expansion of refrigerant from condenser pressure (225 psi) and temperature (105°F) to injection conditions at evaporator pressure (68 psi), and temperature (40°F) will cool the rotors; the lower viscosity of cooling fluid will result in less friction, and a saturated discharge condition will reduce discharge temperatures. Since these compressors tolerate, and by design require, liquid refrigerant injection, the problems experienced in the Fleet with liquid refrigerant floodback will be eliminated.

Reduced energy consumption at partial loads would also be achieved through the incorporation of slide valves in the compressor mechanism. These valves would shorten the effective length of the main rotor during operation at reduced load (Fig. 5), thus matching the compressor to load requirements over a wide operating range.[7]

Positive Displacement Pumps

Unfortunately, pumping an incompressible fluid is a considerably less forgiving process than compressing a gas. Several geometries were investigated; Zimmern attempted a cylindrical main rotor-planar gate rotor configuration in early 1980[6] designs. All of these designs were unsuccessful, suffering from poor suction, low volumetric efficiency, or poor wear characteristics. Development was additionally hampered by the difficulties encountered in manufacturing the complex geometry of the rotors and gate rotors to the required close tolerances. In spite of these difficulties, a major breakthrough was achieved in formulating a concept entitled multi-tooth insertion.[8] This concept has several gate rotor teeth in each main rotor thread, reducing pressure drop across the threads and the associated internal leakage, and improving volumetric efficiency. This multi-tooth design, Fig. 6, also achieves near constant flow with reduced pressure pulsations, thus reducing pump noise and cavitation at high speed. A prototype of this design has been built and is currently successfully undergoing laboratory evaluation.

AIR CONDITIONING SYSTEMS

The Problem

Substantial weight savings and/or energy efficiency improvements can be realized through the use of new materials and new configurations of heat transfer surfaces in air conditioning condensers and evaporators. Figure 7 illustrates the payload weight fraction of a modern combatant; of all the auxiliary systems, the heating, ventilation and air conditioning system represents the largest fraction of system mass and allocated fuel mass.[1] Existing shipboard air conditioning plants use 1.0 to 1.1 kW/ton at full load while modern commercial centrifugal compressor air conditioning plants consume less than 0.7 kW/ton at full load. Advanced air conditioning plants using the single screw compressors previously described and advanced heat transfer surfaces could reduce energy consumption to 0.65 kW/ton at full load. These improvements would result in substantial payoff from reduced energy costs or increased ship's operational range. Energy savings of 1,000,000 kWh/yr are possible for a ship such as an FFG-7.

The Solution—Advanced Heat Transfer Surfaces

New heat transfer tube materials and configurations are now available:[9,10,11]

- Porous coated surfaces for evaporator tubes, which promote nucleate boiling at lower heat fluxes (Fig. 8). These surfaces have pool-boiling heat transfer coefficients of ten times that of a smooth tube (Fig. 9).
- Finned or corrugated tubes, which enhance the surface area and heat transfer coefficient on the water side of evaporator and condenser tubes.
- Titanium tubes, which allow high seawater velocities without erosion or corrosion.

Table 2 indicates the heat transfer coefficients for various configurations of condenser and evaporator tubes.

For these components the Heat Transfer Rate, Q,

$$(Q = U \times \text{Surface Area} \times \text{Log Mean Temperature Difference})$$

is directly related to the Overall Heat Transfer Coefficient, U, BTU/hr ft^2 °F, where for the evaporator or condenser:

$$U = 1/(1/h_{rs} + 1/h_{ws} + 1/h_{wall} + R_f)$$

where

h = heat transfer coefficient
rs = refrigerant side,
ws = water side,
w = wall, and
R_f = fouling resistance factor

Table 2. Evaporator heat transfer coefficients.

Configuration	h_{rs}	h_{ws}	h_{wall}	R_f	U
26 fins/in, smooth, Cooper, 8 ft/s	1500	1300	81282	0	690
Smooth, nucleate, boiling, 95-5 CuNi, 8 ft/s	3200	1300	8330	0	832
Corrugated, nucleate boiling, 95-5 CuNi, 8 ft/s	3200	2200	8330	0	1127

As can be seen in Table 2, changing from smooth, copper tubes, with 26 external fins/in, and chilled water velocities of 8 ft/s, to corrugated, unfinned, 95-5 CuNi tubes, with an exterior nucleate boiling surface, and a chilled water velocity of 8 ft/s, it is possible to improve the heat transfer by a factor of 1127/690 or 1.63 (63%). This would reduce the evaporator weight by almost 50%, resulting in a 2,000 lb reduction per evaporator or 8,000 lb reduction for a modern combatant. Similarly, the seawater velocity can be increased from 8 to 10 ft/s, achieving a heat transfer improvement of 12%.

CENTRIFUGAL PUMPS

The Problem

Design proliferation! The surface combatant fleet has over 28,000 nonportable, nonnuclear centrifugal pumps. While pumps are standardized to a significant extent in form, fit and function, the pump designs are not standardized and there are over 2,100 allowance parts lists (APL's) for these pumps.

Figure 10 presents the range of operating heads and capacities of the centrifugal pumps used in non-nuclear surface combatants. The data points represent the 470 separate performance requirements which are satisfied by the 2,100 APL's. It is significant to note that over 50% of these pumps are 10 horsepower or less.

The Solution—A Standard Family

By considering the overall fleet centrifugal pump requirements, it is possible to develop a standard family of pumps composed of a minimum of configurations. Figure 11 presents the individual operating ranges of a possible family of low pressure pumps composed of four inlet diameters, each having six impeller diameters. These twenty-four configurations could replace the existing 2,172 APL's.

The resultant savings in logistics costs alone could be understated as phenomenal. By going one step further and incorporating the latest pump technology into this standard family, additional payoffs are possible in performance, reliability, maintainability, and initial and life cycle costs. Table 3 lists the features under consideration for inclusion in this standard family of centrifugal pumps.

Table 3. Advanced design features of centrifugal pumps.

Feature	Payoff
Use of Composite Materials for All Wetted Parts	Low initial cost, low life cycle costs, increased erosion/corrosion resistance, reduced weight.
Advanced Hydraulic Design	Improved hydraulic performance, reduced cavitation, improved efficiency, reduced structureborne and fluidborne noise.
Close Coupled Design	Reduced weight and reduced design complexity.
Mechanical Seals	Increased reliability and reduced maintenance.

Composite pumps have been fabricated and laboratory evaluations have been conducted for the full range of potential shipboard loadings. Prototype pump configurations are being evaluated on selected ships as brine pumps. When

evaluations are completed, a standard family will be developed incorporating these concepts.

FIRE PUMPS

The Problem

Shipboard fire mains typically consist of several relatively large centrifugal pumps connected in parallel. To maintain system pressure and to assure ready response to emergencies, one or more pumps are operated continuously. In many ship classes, however, continuous flow demands on the fire main system are often less than 25% of the rated output for just one fire pump. Figure 12 illustrates how operation at such reduced capacities results in system pressures which may rise as much as 30 to 40 psi above desired levels. This results in higher stresses on pumps and piping components, high water velocities through attached heat exchangers, and inefficient operation. Even during high demand conditions, the use of large capacity pumps makes matching of the system design pressure very difficult. As shown in Fig. 12, there are many conditions where the use of one fire pump may not provide adequate pressure (Point B), but the use of two (Point C) significantly overpressurizes the system.

Potential solutions to the overpressurization problem have their drawbacks. The use of a back pressure regulating valve to divert excess flow overboard is inefficient and has the potential to fail open and seriously compromise fire main performance. Many smaller capacity fire main pumps could be used, but that would increase system weight and complexity. Variable speed motors could be used, but the controllers are significantly larger, heavier and more complex.

The Solution—A Variable Capacity Centrifugal Pump

The ideal solution would be to design a variable capacity centrifugal pump capable of producing a performance curve that remains constant over its entire flow range.

The Variable Capacity Centrifugal Pump (VCCP) embodies the features required to do this (Fig. 13). It consists of an impeller with a shroud that changes impeller width in response to system pressure. The cavity between the shroud and casing is sealed by wear rings at the impeller eye (as with a normal centrifugal pump) and at the shroud periphery. Downstream system pressure is fed into this cavity. As the downstream pressure drops, the internal pressure and springs open the impeller, increasing pump capacity. As system head increases, the resultant rise in cavity pressure overcomes the internal forces that close the shroud and reduce pump capacity and it brings system head beack to the desired level.

An existing commercial pump has been modified to incorporate this variable geometry feature. Tests show that this design is hydraulically stable over the range of 500 to 1200 gal/min, providing a constant system pressure within ± 5 psi (Fig. 14). Program plans include the adaptation of this concept to a Navy Standard Centrifugal Fire Pump. The modified pump will be identical to the Navy Standard Centrifugal Fire Pump except for a modified impeller, and a wider, thicker casing to incorporate the movable shroud and wear ring pressure cavity features. If successful, it is anticipated that this pump concept will be used as the lead fire pump for all shipboard fire mains. Other potential applications for this concept include air

conditioning chilled water and air conditioning cooling water systems, both of which have widely varying flow demands at a constant system design pressure.

WATER PRODUCTION

Reverse Osmosis

Reverse osmosis (RO) is a water purification process in which pressurized seawater is forced through a semipermeable membrane, which selectively allows the passage of pure water but excludes the passage of salts.

This process is frequently referred to as the reverse of osmosis, a naturally occurring phenomenon in which pure water separated from a saltwater solution by a semi-permeable membrane tends to spontaneously flow through the membrane, diluting the saltwater, as illustrated in Fig. 15A. An equilibrium pressure, known as the osmotic pressure, must be applied to the saltwater side to prevent this spontaneous flow (fig. 15B). In the RO system, a pressure in excess of this osmotic pressure is applied to the salt or seawater side (Fig. 15C) reversing the flow of water and producing fresh water from the seawater. The RO system incorporates two main elements: (1) a high pressure pump for pressurizing the seawater and (2) a bank of reverse osmosis membrane modules to desalt the seawater. An optional seawater filtration system can be used for the removal of particulate matter to maintain long membrane life.

Reverse osmosis distillation offers significant advantages over traditional methods used in the Navy today; these include reduced maintenance requirements and greater reliability due to modular system design, rapid start-up (minutes), stable performance because of all-electric operation, and 70 to 80% greater efficiency over conventional methods of distillation. In addition, RO plants do not require the use of chemicals for the prevention of scaling, and are smaller, lighter in weight and have lower projected costs as compared to conventional Navy distillation plants.[12,13]

Navy Program

A MILSPEC production prototype 12,000 to 18,000 gallon per day (GPD) RO plant has been designed, fabricated and landbase tested (see Fig. 16). This plant was installed on shipboard in October 1986 and was scheduled for subsequent Technical and Operational Evaluations. The Approval for Full Production is expected in October 1988. The Navy has all rights and data for its MILSPEC production plant. This will allow competitive procurement of Navy RO plants for future shipboard installations.

The Navy design RO plant is shown in Fig. 17 and illustrated schematically in Fig. 18. It consists of a filtration system, a high pressure pump, and a bank of replaceable (spared) RO membrane modules. Seawater is passed through a diatomaceous earth filter used to remove particulate matter, then pumped through the RO membrane modules at a pressure of 700 to 1,000 psi. As the pressurized seawater passes through the membrane modules, 20 to 30% of the flow permeates the membrane as fresh water, and is collected and sent to the potable water tanks. Brine (or concentrate) is discharged overboard through a backpressure control valve. Boiler quality water is produced either by passing water through a *second* RO module *(not shown)* or through a demineralizer. The Navy designed plant will produce 12,000-18,000 GPD of potable water and at least 5,000 GPD boiler quality water.

The capacity range reflects the dependence of the RO processes on seawater temperature. (12,000 GPD at 35°F to 18,000 GPD at 77°F).

A number of preproduction prototype RO plants have been installed aboard US Navy ships.

- A 12,000 GPD plant installed aboard USS FLETCHER (DD-992) in 1981, has logged 15,000 operating hours.
- A 1,200 GPD plant aboard US Navy ship MONOB (YAG-61) in 1983 has logged 3,000 operating hours.

POTABLE WATER DISINFECTION

The Problem

Navy ships must disinfect distilled water to assure that it is bacteriologically safe. On most ships disinfection is done by treatment with chlorine or bromine. Chlorination is one of the most effective ways to disinfect and it has been used by municipal plants for decades. The potential hazards associated with chlorine gas storage however, preclude its use on board ships, and other forms of chlorine treatment such as sodium hypochlorite solutions or calcium hypochlorite powder have had problems. Storage of liquid or solid chemical oxidants in large quantities is potentially dangerous because these agents are unstable, and outgassed chlorine and the powdered materials must be kept dry and away from heat or organic materials. Treatment is also difficult. Batch treatment is labor intensive, requires careful addition of oxidant, mixing, and control of the residual oxidant level, and manual treatment adds the potential danger of inhalation of toxic fumes.

In 1966 the Navy introduced a bromine cartridge disinfectant system to eliminate these potential hazards. This process uses flow through bromine impregnated cartridges to disinfect the potable water. This system resolved many problems; it eliminated the need to store unstable chemicals; it eliminated the necessity of handling hazardous chemicals, and it made continuous treatment possible. Unfortunately, this system also has some major disadvantages. The cartridges have a short shelf life, particularly above 80°F, and are relatively expensive at $30 per cartridge. During a six month deployment of an aircraft carrier, almost 2,000 cartridges would be used at a cost of $60,000.

In addition to the high cost, controlling bromine concentration in the potable water is difficult because bromine's solubility changes significantly with small changes in temperatures. This difficulty is compounded by operations in the Mediterranean and other polluted waters where higher treatment levels are required. Finally, because of system reliability and maintainability problems, many ships have returned to manual chlorine addition.

The Solution—A Simple Chlorine Generator

A state-of-the-art survey of disinfection technologies was performed. Some 50 concepts were investigated representing twelve technologies: microfiltration, ultraviolet radiation, reverse osmosis, nuclear radiation, ozonation, chlorine dioxide bromination, chlorination, iodination, chloramines, and saltwater electrolysis. Onboard electrolytic generation of chlorine gas using a closed cell was selected as the most promising technology.

Figure 19 is a schematic of the cell. The cell is divided into two compartments, an anode compartment containing the positive electrode where chlorine is generated from a sodium chloride solution and a cathode compartment where hydrogen and sodium hydroxide are generated from a sodium hydroxide solution. The compartments are separated by a permeable membrane which allows the sodium cation to migrate from the anode to the cathode solution.

Water and salt are added to the anode compartment, chlorine gas is continuously educted from the anode compartment to treat the potable water, the generated H_2 gas is continuously burned in a Hypolite catalytic burner, and the sodium hydroxide solution must be diluted. Tests indicated that treating 10,000 gallons per day of potable water at a rate of 1 part per million chlorine (1 pound of chlorine per day) requires the addition of 2.25 lb of salt and 1 liter of fresh water per day. To maintain the sodium hydroxide concentrate at an optimum of 8 to 12% requires that 3.7 liters of sodium hydroxide solution generated by the electrolysis, be replaced with fresh water daily. The cell is run at 25 amps, consuming 0.173 kW, and runs at an efficiency of 73%. The cost of salt for this system for a 6 month aircraft carrier deployment would be approximately $600 ($0.10/lb) or 1/100 of the present operating cost.

Although this is an "off-the-shelf" concept and is used in a municipal water treatment plant, some development is necessary to make the system suitable for military application and appropriate for shipboard use. A set of specifications for a shipboard prototype unit have been drafted and a request for proposal (RFP) has been issued. It is anticipated that design fabrication and laboratory tests will be completed this fiscal year and that shipboard evaluations will be completed next year.

NITROGEN GENERATION

The Problem

Oxygen and nitrogen are used in large quantities aboard aircraft carriers to support aircraft. Oxygen and nitrogen generators are typically large cryogenic plants (130 lb/h) requiring significant space (600 ft^2) and electrical power (200 kW). They rely on large high pressure air compressors to provide the air that is expanded in the producer plant; the air compressors are rated at 3000 psi and 1374 lb/h.

The Solution—Molecular Sieve Pressure Swing Adsorption

Molecular sieves are materials that have the ability to adsorb and desorb gas molecules in minute cavities without changing the crystal structure of the sieve. The process is on a molecular scale; entire cavities can be filled with adsorbed molecules rather than only the surfaces of the cavities. Two molecular sieve materials are of interest for oxygen and nitrogen separation or generation: carbon molecular sieves and zeolites.

The pressure swing adsorption process uses the relative attraction and interaction forces of the molecules to separate the gases of interest. For a nitrogen generator, low pressure air (80% nitrogen) is fed into one of two or more beds of molecular sieve. As the bed is pressurized, the molecular sieve adsorbs all the gases; however, each gas is adsorbed at a different rate depending on the sieve material, pressure, and temperature. The oxygen is adsorbed more readily than the nitrogen or argon and the effluent gas is nitrogen rich. The feed process is timed until oxygen is no longer adsorbed. The bed is then depressurized and the oxygen is desorbed and

vented through the inlet of the bed, thus completely regenerating the bed. To provide a smooth flow of nitrogen two or more beds are alternately pressurized and depressurized (Fig. 20).[14]

The Navy has designed and evaluated a two bed nitrogen generation system using a carbon molecular sieve. The carbon molecular sieve material was selected over the zeolite for several major reasons (Table 4):

1. Carbon molecular sieve material has a higher product recovery efficiency, requiring ¼ the input air capacity (although at a higher pressure) of that required by Zeolite;
2. It is insensitive to shipboard contaminants such as water vapor. If flooded with water, the carbon molecular sieve bed can be reactivated after draining the bed and pressure cycling for several hours. A zeolite bed contaminated with water would have to be sent back to the manufacturer for reprocessing;
3. It requires a longer cycle time; ¼ fewer operational cycles are required per unit time, thus significantly decreasing the cycling of valves and timers,
4. Less sieve material is required.

Although design of the pressure swing cycle is relatively straightforward, the design of the high pressure air compressor required to deliver nitrogen at 3000 to 5000 psi is challenging. The Teflon high pressure seal technology developed for Navy high pressure oil free air compressors is being applied to these machines.

Table 5 summarizes the payoffs of a carbon molecular sieve system over a similarly sized current shipboard cryogenic air separation plant.

PIPING AND VENTILATION SYSTEMS

The Problem

Many auxiliary systems and components, including piping, valves, pumps, ventilation ducts, and heat exchangers, suffer significant corrosion and erosion problems and have high life cycle and maintenance costs. Corrosion and erosion of noncritical seawater, bilge water, sewage and chemical waste piping require many costly hours of maintenance including painting, patching, and replacement of deteriorated parts. Some shipboard metallic piping systems, such as photochemical drain lines, have life expectancies of 6 to 12 months. Carbon steel bilge piping is sometimes replaced every overhaul or every second overhaul with more steel piping, creating a wasteful and costly cycle. Severe erosion and corrosion of 90-10 copper-nickel piping systems has resulted in general specification changes for the maximum allowable seawater velocity from 15 ft/s to 12 ft/s.

In new construction, the cost of copper-nickel piping is very high, and in addition lighter piping materials are needed to meet overall weight and moment requirements.

The Solution—Composite Materials

The use of composite materials in shipboard auxiliary systems and components can provide substantial benefits.[15,16]

- Elimination of corrosion/erosion problem
- Reduction of maintenance

Table 4. Comparison of zeolite and carbon molecular sieves.

Sieve Characteristic	Zeolite	Carbon
Oxygen Adsorption Capacity	Low	High
Crush Strength	10 psi	<100 psi
Operating Pressure	35 psi	120 psi
Cycle Time	28 s	120 s
Ratio of Sieve Weight to Weight per hour of N_2 produced	18	10
Industrial Base	None	200 plants
Product Recovery	9%	35%
Bed Pressure Drop	High	Low
Resistant to Bed Fluidization	Low	High
Dusting	Yes	No
Moisture Resistance	Low	High
Navy Experience	5000 h on 4 units 3 Dusting Failures	1800 h on 1 unit 20% Performance Gain
Life	Unknown	>10 years

- Potential for increased strength or fatigue resistance
- Improved damping characteristics
- Compatibility with all hull and structural materials
- Weight reductions of 40 to 80% over conventional materials
- Significant cost reductions, particularly for large systems or components
- Alternative to energy intensive or strategic corrosion resistant metal alloys

Table 5. Carbon molecular sieve advantages. Data show potential payoff from replacing the current shipboard cryogenic air separation plant with two 75-lb/h molecular sieve nitrogen generators.

High reliability	Mean time between failures (MBTF) 2000 h
Improved maintainability	Mean time to repair (MTTR) < 5 h; no 10 to 12 h
Reduced servicing	20 h vs. 64 h per 1000 h operation
Reduced manning	Manual startup with automatic unmanned operation vs. 2 operators/shift
Reduced costs	\$0.7M vs. \$1.7M machinery costs
Reduced weight	20,000 lb vs. 67,000 lb
Additional ship weight/ cost savings	No need for the lb/ft^2 protective floor that cryogenic plants require
Reduced area	120 ft^2 vs. 1300 ft^2
Less input air	420 lb/h at 120 psi vs. 1374 lb/h at 3000 psi
Reduced energy consumption	1440 kWh/day vs. 4500 kWh/day
Safety	No cryogenic fluid hazard

The need for a corrosion-free, lightweight, low cost, alternative to metallic piping aboard advanced Navy ships provided an opportunity to investigate composite piping materials. The PHM class now has glass reinforced plastic (GRP) piping and a military specification for pipe and fittings now exists.

This specification controls materials, configurations and dimensions as well as performance requirements in order to provide standardization glass reinforced plastic piping systems which would be compatible with Navy standard requirements for new

and advanced naval ship construction as well as the overhaul and retrofit needs of the existing Fleet.

The components detailed in the military specification have been designed with the goal of inherent fire, fatigue, shock, and corrosion resistance. The specification contains no proprietary information and was developed from the standpoint of promoting maximum commercial competition.

GRP is considered to be a prime candidate substitute for copper-nickel, copper, and lead lined carbon steel piping and is authorized by the General Specifications for use in the following piping systems in sizes up to and including 6 inch:

Seawater Cooling and Flushing Systems

Distilled Water Systems

Main Drainage

Secondary Drainage

Potable Water

(Non-Vital) Chilled Water

(Non-Vital) Low Pressure Air

Oily Water and Wastewater Collecting

Deck Drains (except for flight and hangar deck and helicopter platforms)

Plumbing Vents

These systems in pipe sizes up to and including 6 inches nominal diameter represent a large percentage of the water piping systems currently found aboard conventional naval surface ships. Figure 21 compares weight of GRP piping with various metallic piping materials in the 1- through 6-inch size range, and shows that GRP is the lightest piping on a weight per foot basis. Figure 22 indicates that GRP is generally comparable with CuNi on a cost basis.

Valves, fittings, and other factors must be considered to determine if GRP can actually reduce the weight of a piping system. A 1971 study for the Patrol Frigate class showed that a GRP system including fittings was about one-third the weight of a steel or copper-nickel system for a weight saving of about 22 tons per ship. This evaluation considered piping of 6-inch and smaller diameters.

The military specification is being updated to include impact and shock resistance data and guidance. Smoke, fire and toxicity studies are being conducted on protective coatings and pipe jacketing materials which will enhance shock and fire protection, and high temperature adhesives that will allow the use of GRP above the 150°F maximum are being evaluated.

Substantial payoffs and savings are also possible with other components. Figure 23 demonstrates the cost and weight savings possible using composite ball valves, and Table 6 illustrates the potential weight and cost savings which could accrue from using composite ventilation ducting on a modern combatant.

An innovative application of composites is to replace the copper alloy seawater heat exchanger and condenser tubes in surface ship air conditioning system seawater cooled condensers, which have been subject to severe corrosion and erosion problems. The inherent corrosion and erosion resistance of many plastic and polymer matrix composite materials has been successfully utilized by the chemical processing industry. Although the use of plastic and composite materials does not immediately suggest itself as a viable alternative due to thermal conductivity concerns, certain

combinations of conductive filters, reinforcements, and plastic matrix materials appeared worthy of detailed assessment to define their limitations and compare their effectiveness with copper-nickel and alternative metal alloys. Figures 24 and 25 present relative measures of effectiveness of various materials which could be used as heat transfer tubes. These measures are a function of the allowable stress level (SA), radial thermal conductivity (K), and density (P) of the material. Figure 24 indicates that composites can be competitive with titanium and 70-30 CuNi when strength and conductivity are considered. When weight or density is considered, Figure 25, the composites become even more attractive and are competitive with Inconel 625 and 90:10 CuNi.

Table 6. Assessment of GRP ventilation ducting on modern combatants.

Concept	Weight Savings (lbs)			Estimated Cost* of GRP Supply System Vent Ducts		
	Replaces Aluminum	Replaces Steel	Replaces Both	Unit Cost ($/lb)	Weight (lb)	Cost ($K)
Sprayed glass fiber & resin	− 253	8,243	8,496	1.50	9,593	14.4
Sandwich GRP skins, honeycomb core	2,234	11,415	13,649	16.70	4,440	74.1
Double GRP wall with internal ribs	− 1,757	5,077	3,320	3.00	14,769	44.3
Sandwich GRP skins with foam core	1,958	10,984	12,942	3.00	14,769	44.3

*Excludes developmental, installation and anomalous costs as well as the economies of large procurements.

ELECTRIC PLANT: OVERVIEW

The Ship Service Electric Plant encompasses the prime mover generators and the conditioning, conversion, protection and distribution equipment necessary to power the wide variety of vital and nonvital loads. The preponderance of power in future surface combatants will remain 450 V, 60 Hz ac but one or more varieties of specialized power (currently 400 Hz) will be available for combat systems and other critical equipment. This specialized power, be it 400 Hz or direct current as discussed

later in this section, will be generated locally, (e.g., near vital load centers or within user equipment or its spaces) with solid state equipment powered from 60 Hz feeders. Power system architecture, at all frequencies, will reflect the unique interface requirements of increasing power levels of nonlinear, or switching loads.

Current R&D thrusts in ship service machinery areas emphasize providing high quality, closely regulated power with improved continuity and system/load compatibility; increased power generation, conversion and load efficiency, and reduced weight and volume. Taken together, these will permit ships of increased range or increased payload fraction, as well as improved combat system readiness.

Electric machinery developments targeted for future surface combatants can be grouped into power generation, distribution system, and load equipment areas, and they are discussed under these headings below. Included under *Electric Power Generation* are advanced simple cycle gas turbines as well as higher efficiency recuperated (and intercooled) units. Rotary engines which promise the compactness of gas turbines at diesel engine costs are covered. Also addressed are electric generation systems designed to be driven by the ship propulsion engines.

Items discussed under *Distribution System Hardware* include (battery powered) uninterruptable power supplies (UPS) to assure power continuity (and in some cases required voltage/frequency regulation) to vital circuits. Rapid response breakers, current limiters and fast bus transfer equipment can minimize the consequence of failures or damage. Finally, the concept of providing combat and other vital systems with direct current (dc) power is discussed.

Auxiliary drive motors without disruptive starting surges and variable speed drives are addressed under *Electrical Load Equipment*. Hardware benefiting from superior cooling or new materials are also under development.

ELECTRIC POWER GENERATION

Engines for Ship Service Power

The role of the modern combatant in today's Fleet has placed increasing demands on the quality and quantity of electrical power generation. As the size and number of generator sets increase, so does the impact of engine operation and performance on ship mission effectiveness. Generator set engine selection therefore should be based on total ship impact and cost considerations. The following engine characteristics are desirable:

- Low acoustical, thermal and magnetic signatures to reduce the threat of detection in a warfare environment.
- Good, dynamic response to meet electrical load requirements (minimize frequency transients and recovery time).
- Low fuel and air consumption to minimize ducting and tankage requirements.
- Modular construction for ease of removal and depot overhaul, thereby reducing shipboard maintenance and manning.
- Low weight and compact size.
- Low acquisition cost.

Shipboard engines are required to operate at part load conditions during most of their service life. For gas turbines, part-load thermal efficiency and fuel economy are reduced by as much as 30% from the full power design condition. Marine diesel

engines have improved thermal efficiency but are physically massive and require large engine foundations to reduce structureborne noise. Future low observable ships will require lightweight, compact engines that can be silenced with small foundations thereby alleviating a space shortage for weapons payload. In all shipboard applications, engine reliability, maintainability, and availability are critical to ship mission effectiveness, especially under combat or emergency situations. To achieve this operational readiness, engines require long-life components that can operate under off-design or degraded conditions and that minimize the maintenance burden by using modular design techniques.

The U.S. Navy has traditionally relied upon commercial engine developments as a technology base for selecting ship service prime movers. This approach is essential to insure that acquisition and logistical support costs are affordable over the ship's life cycle, and that advanced engines are utilized to achieve superior operation and combat capability. Emerging materials and design improvements from commercial, aerospace, and military developments are being evaluated to benefit ship service engine efficiency, reliability, and power density in two key areas:

1. Gas Turbines. Application of recuperation of waste heat from the exhaust gas is projected to reduce ship mission fuel requirement by 10 to 15% for a typical mid-sized combatant. In addition, infrared signature is reduced by a significant decrease in engine exhaust temperature.
2. Diesels. Application of emerging rotary engine technology as a replacement for piston and crankshaft functions is expected to reduce generator set size and weight 30 to 50% (see Fig. 26) while preserving thermal efficiency and fuel economy. Modular engine construction will facilitate removal and depot overhaul, thereby reducing shipboard maintenance and manning.

A qualitative assessment of these concepts (relative to currently used gas turbine technology) is provided in Fig. 27 and in Table 7.

A Navy effort to develop a fuel-efficient, recuperated gas turbine will build upon other military and commercial developments. The Army Tank Command is involved in the development of gas turbines (see Fig. 28) with good part load efficiency (tank engines operate at low power levels a considerable portion of their life); and the production quantities involved in this application provide a good, logistical base. Several manufacturers have developed or are developing recuperated gas turbines for the commercial, industrial or marine market, and these efforts have potential application to Navy needs. The present Navy development program plan addresses technology development and selection of candidate commercial engines which will meet electric load requirements, have a positive ship impact, and provide attractive life cycle cost:

- Dynamic Response Testing and Analytical Model Simulation. Initiated in 1985, this effort will determine what system control requirements are necessary to meet the dynamic response requirements of shipboard generator-set loads. A steady-state and dynamic model is being validated by Navy tests of candidate military and commercial engines.
- Ship Impact and Life Cycle Cost Trade-Off Study. Beginning in 1986, competitive feasibility studies will be initiated to establish attractive gas turbine, diesel, or rotary engine options. Manufacturers will be asked to define conceptual designs that best meet Navy shipboard requirements of

Table 7. Assessment of ship service engine candidates for future midsized combatants (circa 2000).

Major Characteristics	Rotary*	Recuperated Gas Turbine*
Acquisition cost	+	–
Maintenance burden	–	–
Fuel economy	+	+
Size and weight	–	–
Transient response	0	0
IR Signature	+	+
Magnetic Signature	0	–
Acoustical Signature	–	+
Tolerance to degraded fuels	+	–

*Rating comparison to baseline = current shipboard simple gas turbine technology. The symbol + is favorable; 0 is no change; – is unfavorable.

performance, physical characteristics, and cost. These results will be utilized to determine total ship impact and to develop life cycle costs for a nominal baseline combatant. Future studies will focus on reducing signature emissions to reduce operational detectability.

The Navy is also pursuing rotary engine technology under development by industry and other government supported efforts. Both NASA and the U.S. Marine Corps currently have active programs to develop rotary engines for use in general aviation and amphibious landing craft vehicles, respectively. Both programs are using the stratified charge concept owned by John Deere Technologies International (JDTI), which allows efficient combustion of a wide variety of fuels. The Navy program will extend these developments to meet the need for increased shipboard operating life [3000 to 6000 hours mean time between overhauls (MTBO)] and to reduce engine vibration and structureborne noise. Navy and JDTI seal wear and housing coating test programs are currently underway to identify materials and engine operating conditions necessary to meet the extended life requirement. Results will be used to design a test engine, which will later be built and operated for verification of performance, endurance and noise predictions. Initial R&D testing of the Marine Corps engine design (Fig. 29) will begin at DTNSRDC in 1987 and will

provide technology exchange between the Navy program and Marine Corps Development programs (see Fig. 30).

The advantages of drawing ship service power from the propulsion power train have been known for many years. A major incentive for *Propulsion Derived Ship Service* (PDSS) is to reduce fuel consumption since the incremental fuel rate of the propulsion engines is generally better than that of small individual prime movers dedicated to ship service. (This is especially true for current technology simple cycle gas turbines in ship service turbine generator (SSTG) applications, but would be less so if advanced heat recovery and intercooling techniques are applied to SSTG's, as discussed above.) A second motivation for PDSS is to reduce the number of installed engines for ship service power, thereby reducing maintenance and operational costs.

There are several ways to generate the required 60 Hz, 450 V power from the propulsion system. The simplest from an electrical standpoint is to use a constant speed generator. This imposes some rather undesirable operational limitations on the propulsion prime mover. If the propulsion engine speed cannot be varied while the PDSS generator is operating, either the propulsion transmission system must have a variable ratio capability or the operation of the PDSS is limited to a single ship speed. Electrical power generation at a single ship speed is viable for merchant ships making passage from port to port, but of questionable value to a combatant ship with large speed variations in its operating profile. Achieving an efficient continuously variable propulsion transmission ratio is extremely difficult by any means other than an electric drive.

A more practical means of providing PDSS is through use of a variable speed constant frequency (VSCF) generator.[17] A VSCF generator provides a constant frequency output with variable speed input through the use of power electronics. This may be done through a number of configurations, using a number of different component types. One configuration is a doubly-fed induction generator, as shown in Fig. 31. The power electronics in this configuration are inserted in a feedback loop between the generator output terminals and the generator field windings. This allows the electronics to be sized to handle only the slip power of the induction generator and still maintain constant frequency output. If the operating speed range is narrow, the rating of the power electronics may be substantially less than the output of the generator. As the speed range increases, however, the power that the electronics must condition also increases.

Figure 32 indicates another approach which is to simply apply the power electronics to the output of a synchronous generator. In this case the power electronics must, obviously, be sized to match the generator rating. VSCF systems provide the advantage of excellent frequency and voltage regulation through the use of power electronics. Although this is done at the expense of harmonic distortion from the electronics which must be filtered to provide adequate output power quality, the VSCF synchronous generator-full power converter approach has the greatest versatility with the highest speed range capability. Also, because of the high speed generator, significant weight savings could be obtained as compared to conventional generator designs.

A 100 kW scale model with full power solid state conversion is shown being readied for laboratory evaluation in Fig. 33. Full scale prototype hardware will be evaluated in FY 1990 and approval for production (AFP) is anticipated in the early

1990's. One likely arrangement of VSCF generators in a twin shaft four engine ship is illustrated schematically in Fig. 34.

DISTRIBUTION SYSTEMS HARDWARE

An increasing selection of advanced limited-break and no-break battery backup power sources, such as the 250 kVA *Battery Energy Storage System (BESS) illustrated in Fig. 35, will be available to designers of the next generation of ship service electric systems. These systems, which could be either (switchable) standby units (like BESS) or on-line designs as illustrated schematically in Fig. 36, would provide a continuous or minimally interrupted source of power to vital loads when primary power fails. This failure might be at the generator itself, or in the distribution system, and backup power units might be co-located with generators or distributed within the ship service systems with a likely survivability benefit. Continuous (no break) power units are not* likely to be located with generators.

One motivation for development of off-line limited break power supplies like BESS is to provide a passive or fuel independent alternative to operation of redundant prime movers as a (rotating) power reserve. (This fuel inefficiency of turbine generators at low power levels is most pronounced when current technology simple cycle turbines are considered, as discussed elsewhere in this paper.) A second benefit anticipated from a BESS is to improve the continuity of power within specified quality limits to a ship's sensitive electronic loads, thereby reducing down times of these systems.

The BESS, a standby power unit, could come on line within one millisecond of a detected power interruption or designated "out of spec" condition. It incorporates power transistors in a step-wave converter capable of bidirectional power flow, to serve as both inverter (when BESS is to supply power) and battery charger (when BESS is on standby). Delivered power would meet DOD-STD-1399, even with a 50% non-linear load. Silicon-controlled rectifiers would be used in the bus-transfer switch which is part of the BESS system. The battery. which would provide sufficient capacity, at a minimum, to allow a cold turbine generator to be brought on line, would be of a rugged, nonvented lead acid construction.

BESS hardware is being developed for the Navy by Teledyne Inet after a competitive design phase. Brassboard tests will be completed in FY 1988 along with specifications for full-scale prototype development. The Navy will own all data rights to the BESS electronics and production units will be procured competitively.

Considerable attention is being directed at a dc system dedicated to vital combat system loads, and such a system might be available for the next generation of surface combatants. Proponents of such a system point out that since most well regulated 400 Hz power is rectified and reconditioned in the load equipment, supplying these largely electronic loads directly with direct current should result in reduced system weight and complexity. Elimination of costly 400 Hz power conversion equipment and rectification hardware would provide considerable topside weight savings in future ships.

One such dc system concept is shown schematically in Fig. 37, along with the 60 Hz system which powers the dc legs. The combat system would be broken down along the lines of high and lower power loads. The lower power combat system loads would be supplied with 155 and/or 270 V dc, with 600 V for high power loads. The

high powered high voltage loads would include high voltage power supplies for sonar equipment, radars, and electronic warfare equipment. The low voltage power would be supplied to digital logic, controls, and other lower power applications. The 155-165 or 270 V dc bus would be stabilized by a dc-to-dc regulated converter powered by a battery bank with sufficient capacity to maintain the bus within specified power quality limits for 2-3 minutes or longer as required. This would cover the time during and after the interruption of a normal power source in a manner analogous to BESS operation in the 60 Hz system. The high voltage bus would be stabilized on the alternating current system side by either a fast automatic bus transfer (ABT) switch with a switch speed of on the order of 1-10 ms or by a BESS unit with a similarly fast switch. Also, the high voltage may be provided only by conversion within the loads. As a third alternative, auctioneering or OR'ing diodes which can switch as fast as 0.300 ms would be used on the 600 V dc side of the normal and alternate converters. Significant weight savings are projected for the dc systems especially in power conversion equipment, battery backup systems and user equipment converters. Energy savings also results from the conversion of generated electrical power directly into the dc power required by the loads.

A variety of new or improved components are under development which are intended to improve power quality and compatibility between the distribution system and user equipments and to assure greater survivability and maintainability. *Advanced Design Circuit Breakers* using insulated molded cases and fast response solid-state trip circuits will be available in increased interrupting capacities (up to 150 kA). Size, weight and costs of this family are expected to be 40 to 70% less than current units.

Current limiters incorporating pyrotechnic elements, such as the unit shown in Fig. 38, will be available for bus tie circuits within action coordinated with breakers. When a fault current is sensed which would exceed the breaker ratings, the device would be triggered to limit maximum current to below breaker ratings, the device would be triggered to limit maximum current to below breaker capacity, allowing the breakers to safely sectionalize the plant. Typical performance is illustrated in Fig. 39. Another type of fault current limiter switches as a controlled impedance into a circuit that has developing short. This operation maintains current drain and voltage dips to within specified quality limits and allows coordination of power distribution system protective devices. A unit of this type, for 400 Hz service, is shown in Fig. 40.

Improved response bus transfer switches are also under development as are system level improvements such as "smart" controllers, which could rapidly integrate and coordinate the action of sensing and system reconfiguration hardware to suit mission priorities.

ELECTRIC LOAD EQUIPMENT

Many voltage dips in shipboard power systems are caused by the starting inrush current of large motors. The inrush current on a power system of limited capacity must be controlled to avoid voltage transients and their associated problems, especially in sensitive electronic equipment. On future ship systems inrush currents in large ac motors can be limited by utilizing a family of military reduced voltage/current *Ramp Motors Starters* now under development. The family, consisting of four 440 V, 60 Hz units rated at 50, 100, 200 and 400 hp, will utilize

solid state devices to provide stopless, controlled rate of rise of motor starting current.

Standardized solid state *Speed Controllers* are also envisioned for auxiliary drive motors. Power levels of 125, 250 and 500 hp are planned with capability for a 10:1 speed range. The systems should be attractive alternatives to fixed speed pump or compressor motor applications, which require mechanical throttling, on-off cycling or bypassing. They might also find application where hydraulic systems are now employed.

New materials are also being introduced to improve component performance. One example included the application of amorphous metal to *Shipboard Transformers*. Reductions of 55% in power losses, 50% in weight, and 23% in volume have been projected relative to current shipboard units.

MAIN PROPULSION MACHINERY: OVERVIEW

For the first half of this century, mid to large size combatants relied primarily on steam propulsion systems that consumed a significant portion of the ship's volume, weight, and manpower. In the 1940's, the US Navy began exploring gas turbine propulsion with potential for higher efficiency and more favorable ship impact. Early efforts to develop this concept were impeded by its unproven reliability and lack of established logistical base.[17,18] Over the next two decades however, advances in gas turbine materials, design techniques and performance have led to its wide acceptance in the industrial and aviation industries. Capitalizing on this broad commercial base, navies worldwide have now adopted the gas turbine as a cost-effective, reliable prime mover for most combatants.[19]

The gas turbine is perhaps the most revolutionary change that has happened to naval propulsion systems over the past fifty years, influencing the design of gears, control systems, transmissions and propellers. As a total system, propulsion machinery and fuel can strongly influence overall ship design and mission effectiveness. For a mid-sized combatant, the propulsion suite can occupy over 25% of the total ship volume and displacement, and affect over 35% of its total operating and service cost.[20,21] Consequently, propulsion system developments discussed in this section are focused toward benefiting the total ship mission needs:

- Enhance warfare capability
  - Reduced gas turbine exhaust temperature
  - Quiet gear design
  - High performance contrarotating propellers
- Ship affordability over life cycle
  - Lower fuel consumption
  - Increased prime mover tolerance to degraded fuels
  - Reduced maintenance
- Increased firepower and weapons payload because of reduced machinery weight and volume
- Enhanced arctic operations capability through increased resistance to ice impact with ductile composite propeller shaft.

This section discusses *Gas Turbine System Developments* which are expected to evolve for the US Navy RDT&E pipeline and be candidates for ship design contracts

in both the near-term (circa 1990) and mid-term (circa 1995). Future technology and design thrusts are identified as they relate to the following major subsystems:*

1. Main propulsion gas turbine and module
2. Integrated electronic control (IEC)
3. Inlet air ducting (includes air filters and silencers)
4. Exhaust ducting (includes infrared suppressors)
5. Waste heat recovery system

A gas turbine module installation is illustrated in Fig. 41. When repair or replacement is required, the modular design of the gas turbine facilitates removal through the air inlet ducting as shown in Fig. 42.

The last part of this section identified mechanical and electrical transmission systems developments that are expected for ship design contracts about circa 2000. To a large extent, development will depend upon our ability to apply advanced aerospace materials and manufacturing technology to ship requirements. In most cases, technology readiness has been demonstrated, and future efforts are needed in design demonstration/validation and full-scale development. Figure 43 identified the chronological order of major subsystem developments expected to evolve from the Navy RDT&E process, wtih eventual integration into a total propulsion system test site.

GAS TURBINE SYSTEMS

Background

Today the simple cycle gas turbine is the preferred choice for propulsion on most mid-sized naval combatants; future estimates suggest that by the twenty-first century almost all US Navy ships will be powered by gas turbines (Fig. 44). This wide acceptance is due primarily to the demonstrated engine reliability, rapid start-up, simplicity of design, ease of maintenance, low noise, and high performance. As illustrated in Fig. 45, the engine's rotary blades axially compress air in multiple stages for high pressure combustion of fuel, and expansion through an axial turbine, producing shaft power for the gas compressor and external power (about ⅔ of the available shaft power is used by the compressor). Figure 46 identifies the thermodynamics cycle (a Brayton cycle) of gas compression, adiabatic combustion, and expansion through the turbine. Gas turbine machinery has progressively improved over the past four decades to a level where the simple cycle efficiency is about 30%.

Near Term Developments

The US Navy now relies primarily on the simple cycle LM2500 (Fig. 46) nominally rated at near 21,000 to about 27,000 shp at Navy standard conditions.** A marine version of the TF-39/CF-6 aircraft engine developed in the 1960's, this engine

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*Additional auxiliary systems required to support the gas turbine have been the focus of numerous development efforts but will not be discussed here; these are fuel oil system, lube-oil, bleed-air, cooling, and anti-icing waterwash, drain, air-start, and fire protection systems.

**100°F ambient temperature with inlet and exhaust ducting losses of 4 and 6 inches pressure loss, respectively.

currently enjoys the largest industrial and marine production base in the free world. Its extensive operating experience has led to improvements in materials and design that have been the focus of a major Navy effort initiated in the mid-1970's, the LM2500 Component Improvement Program (CIP). This program successfully reduced operating costs through improved engine component reliability and increased mean time between removal (MTBR) with future levels predicted at 10,000 hours.

Through early identification of service related engine difficulties, CIP has initiated major improvements in the following areas:

- LM2500 single shank turbine blade development--replacement of paired airfoils to increase turbine MTBR and reduce engine vibration without production cost increase.
- Development of onboard repair procedures for increased life and performance of compressor blades, variable stator vane bushings, electronic engine overspeed control, and main fuel control.

The LM2500 CIP is planning further improvements over the next five to seven years:

- Improve bearing damping design
- Improve fuel control system dynamic response
- Lengthen life of power turbine casing (>10,000 hours)
- Improve gas turbine enclosure to reduce ambient noise and module wall temperatures
- Increase turbine blade coating life by a factor of two
- Increase engine tolerance to degraded fuels having increased concentrations of sulfur and vanadium.

A major new thrust of the Navy gas turbine development program affecting not only the LM2500 but also future generation engines is a new integrated electronic control system (IEC) utilizing recent improvements in microchip circuitry.[22] This system replaces the previous hydromechanical control, which has been a high maintenance item. The new digital IEC is designed for rapid signal processing of vital engine parameters (i.e., temperatures, vibration, etc.) and operator control inputs; rapid processing features and early warning failure indications without engine shutdown will improve engine availability and MTTR. In addition, the fuel and variable stator vane scheduling will be removed from the engine/fuel environment entirely to a separate control unit. A development program, scheduled to impact the DDG 51 Class, includes design, fabrication, procurement, and component qualification testing, as well as system land based testing by the Navy. Figures 47 and 48 show the IEC system elements and arrangement.

Mid-Term Developments (Circa 1995-2000)

Since the Navy committed itself to gas turbine propulsion, the diminishing worldwide fuel supply has focused attention on more fuel-efficient engines for the future. For simple cycle engines like the LM2500, considerable energy can be gained by use of a waste heat recovery system in the hot exhaust gases (near 1,000°F). In the mid 1970's when fuel costs began to rise, the US Navy began development of a recovery system (called RACER, Rankine Cycle Energy Recovery)[23,24] to convert exhaust gas energy to useful medium pressure steam as an add-on to the current

LM2500 propulsion system (Fig. 49 and 50). The added ship horsepower derived from this COGAS (combined gas and steam) arrangement (Fig. 51) reduces main engine load requirements with consequent savings in fuel consumption of about 20%. This benefit is achieved at the sacrifice of increased machinery weight (over 150 tons) and a commensurate volume growth. Since the early 1980's, the Navy has contracted for full-scale hardware testing of the system, with land based testing the next step in demonstrating the performance and reliability needed aboard ship. Unfortunately, the high technology required to meet these requirements have increased system costs to the point where life cycle cost benefits are diminished. Only the future will tell whether the ship impact is worth the additional investment.

Since the development of the LM2500 over twenty years ago, more efficient, advanced technology engines have evolved in the commercial market; these new engines are smaller, lighter, have fewer moving parts, and lower operating costs (see Fig. 52). As these engines replace the current LM2500 production base, the Navy will be faced with increasing acquisition and logistical costs in its effort to maintain a supply of LM2500's (currently less than 30% of the world market). To offset the burden, the Navy will need a new generation of marine gas turbines based on new commercial based engines in use about the time the LM2500 goes out of production (predicted near the turn of this century). A strong commercial production market is required to insure adequate logistical support over the life of the next class of combatants.

Since combatant main propulsion turbines are required to operate at part load conditions for most of their service life, simple cycle specific fuel consumption can be over 40% higher than at design (or full power) levels. Some method of energy conservation is required, therefore, if the next generation of gas turbines is to be cost effective. A common practice in commercial applications involves the use of an air-to-air heat exchanger (recuperator) placed in the exhaust gas duct to transfer heat from the hot exhaust gases to the cooler air entering the gas turbine combuster. As shown in Fig. 53, this process reduces the amount of fuel needed to raise the compressed air to the necessary working temperature of the turbine. Recuperating an existing simple cycle gas turbine can increase the cycle efficiency by 20% without requiring advances in the basic core engine technology.[25] An added benefit of reducing the exhaust gas temperature is the considerably lower infrared signature at the top-side gas stack, a major benefit in covert warfare operations. As shown in Fig. 54 and 55, candidate high-efficiency recuperators are currently being evaluated for the next generation of marine turbines[26,27,28]; efforts are directed toward minimizing recuperator weight (currently less than 20 tons) while maintaining high thermal effectiveness. The final recuperator will utilize advanced materials and commercial design experience to minimize induced fatigue stress from thermal transients and dynamic shock loads.

The next generation of high-efficiency Navy gas turbines will utilize core engines developed from high compression commercial engines[29]. If, in addition, these engines are recuperated, some method is required to reduce the high compressor air temperature to a point where heat can be effectively transferred from the gas turbine exhaust. This is achieved by using a heat exchanger (called an intercooler) to cool the air midway through the compressor so the work of compression is reduced; this savings can be significant since two out of every three horsepower generated by the turbine is used in air compression. For high compression ratio engines, the

intercooling effects significantly increase overall gas turbine thermal efficiency (Fig. 56) and correspondingly reduces compressor size. A typical tube-in-shell intercooler illustrated in Fig. 57 adds less than 50 tons to the engine system. Overall hardware arrangement for an intercooled, recuperated advanced gas turbine is shown schematically in Fig. 58. An additional performance benefit can be achieved by using current technology, variable area power turbine vanes (VAT) for improved part load fuel economy, Fig. 59.[30] VAT optimizes turbine operating conditions for efficient part load performance during most of the ship's mission profile. Engines modified with VAT, intercooling, and recuperation can produce fuel savings over 30% compared to simple cycle engines[31] and exceed fuel economy predictions for the RACER (COGAS) system.

For the ICR gas turbine (Fig. 60), numerous studies have been conducted to quantify the ship and cost benefits of the ICR gas turbine. Quantitative results can vary considerably depending upon assumptions, such as mission priorities, baseline ship selection, machinery suite, etc. In most cases, however, the ICR engine benefits of IR suppression and reduced fuel consumption outweigh the added development costs and machinery weight/space penalties. In general, results of such studies suggest that for a mid-sized monohull combatant with twin shafts (two or four engines per ship, LM2500 baseline), and equal mission capability, the ship impact of ICR engines can be characterized as follows:

- 20 to 35% annual fuel savings
- Full load displacement reduced (approximately 3%)
- 5 to 7% lower annual operating costs
- Reduced life cycle cost with positive return-on-investment
- Top-side gas turbine exhaust temperature and IR signature reduction
- Reduced top-side/deck house noise from turbine exhaust

The ICR core engine is projected to be smaller and lighter than the LM2500, which will help offset weight increase from the added recuperator and intercooler. Since the new engine enclosure will fit the same base foot print as the current LM2500, backfitting into existing gas turbine ships is feasible. Fleet introduction of this new third generation engine is not expected until the midnineties, so the first new class of combatants to benefit from this design could be the DDG-51 (Flight III). All subsequent displaced hull gas turbine powered ships should be considered candidates for the ICR engine.

POWER TRANSMISSIONS

To meet Fleet anti-air and antisubmarine warfare threats, future surface ship combatants will require power transmission systems designed primarily for low acoustic and nonacoustic signatures. This type of design becomes increasingly difficult in new hull forms, that use submerged pods or nacelles where space constraints necessitate high power density components. This problem is further compounded by the trend toward lower rpm operation, which causes higher torque and stress levels for size-limited shaft line components. To address these requirements, Navy R&D efforts are focusing on propulsion train elements having major ship impact in reducing noise, cost, size, and weight.

Reduction Gears

In the near term, conventional locked-train, double reduction (LTDR) gears will continue to be the dominant speed reducer between the prime mover (gas turbine at 3600 rpm) and propeller (at 120 rpm or lower). An increasing requirement to reduce machinery size and weight has led to developments in the application of surface hardening and grinding, beyond the traditional small pinion gears, to large, second stage, bull gears over 100 inches in diameter. Most US Navy bull gears are currently through-hardened with limited surface hardness and tolerance to local compressive stresses (corresponding to the index of load intensity, K, of 110 to 130). The size of a main propulsion gear box is strongly influenced by the bull gear size, which, in turn, is a strong function of the K factor. The weight of a typical LTDR gear box versus K factor is shown in Fig. 61. Since the next generation of gas turbines is expected to be smaller, the development of high K factor gears will allow smaller, more compact machinery arrangements (see Fig. 62).

The US Navy is evaluating both US and European gear design manufacturing technology in an effort to develop cost-effective, high K factor gears. Three methods of case hardening, each producing different depths of hardness (Fig. 63) and load bearing capacity, are being considered:

1. *Carburizing*: Best load carrying capacity; heat treatment transforms the high carbon case to a very hard surface, Rockwell Hardness (Rc) above 60.[32] Subsequent tempering reduces hardness and relaxes residual stresses. Although acceptable for small gears, carburizing can produce distortion levels unacceptable for large gears, particularly when quiet operation is required.
2. *Nitriding*: Low distortion levels; as shown if Fig. 63, this process produces a shallow case depth and loads must be kept low enough so the core material can carry the subsurface shear stresses. Since processing temperatures are low and no quenching is involved, distortion is minimal.
3. *Induction Hardening*: Deep case hardness, low distortion and sharp discontinuity in hardness at the case-core boundary. For this reason larger teeth are required to allow the induction coil process to push deep into the tooth.

Increasing tooth loading can also increase the potential for noise generation. Consequently, hardened and ground gears require close control of heat treatment and manufacturing processes for low distortion and accurate gear tooth tolerances. Although gear tooth manufacturing has progressed significantly over the past decade, tooth surfaces lack perfect spacing and profiles, especially at operating loads and temperatures. To minimize inaccuracies and the resulting vibration and acoustic levels, US Navy gear design has traditionally used fine pitch teeth with helix angles up to 45°. Additionally, the design philosophy of the European community suggests that axial contact ratio (number of teeth in simultaneous contact) strongly influences gear tooth acoustics and should be a whole integer. Both European and US design approaches are supported by the gear design theories set forth by W.D. Mark.[33,34]

In an effort to capitalize on the benefits of both design approaches, the US Navy, in cooperation with both US and European gear manufacturers, initiated a large gear development program to improve our ability of producing quiet marine gears. Various types of materials, heat treatment, gear construction, and tooth size and shape are being evaluated in land-based testing of full-sized naval propulsion

gears under typical operating loads. Initial test results correlate favorably with noise levels predicted analytically, and have led to a better understanding of design features and tooth error patterns which dominate the acoustical spectrum. Results of this continuing program will help formulate quiet gear design methodology for future Navy combatants.

Mechanical Reversing Systems

Since the widespread use of main propulsion gas turbines, the controllable, reversible pitch (CRP) propeller has been accepted as a standard method of reversing aboard US Navy combatants. Although the CRP propeller provides adequate reversing, maneuverability, and low-speed power scheduling, two disadvantages have become of increasing concern:

1. CRP propellers require large supporting appendages and shafts which reduce operating efficiency and impose penalties of reduced range.
2. Propeller maintenance requires expensive drydocking for inspection and repairs.

Since the early 1970's the US Navy explored reversing gear concepts to permit use of the more efficient fixed-pitch (FP) propeller and reduced drydocking requirements for inspection and periodic repairs. Three reversing gear designs were considered where reversing was accomplished by either a torque converter or a friction brake/high speed epicycle gear arrangement. High speed clutches were used to switch from ahead operations to the maneuvering regime. After initial design studies, full-scale testing continued on the reversible-hydraulic-coupling system designed by Franco-Tosi of Italy, and similar to that used by the Italian Navy on their aircraft carrier Garibaldi. As shown in Fig. 64, the Franco-Tosi reverse reduction gear (RRG) is basically an add-on unit with very little modification needed to the standard double-reduction locked-train propulsion gear. The reversing coupling is installed on the second reduction shaft for each turbine. Maneuvering and reversing action is initiated by first adding fluid to the hydraulic coupling and then reversing the direction of the fluid by inserting a reversing vane (see Fig. 64). An important operating characteristics of the RRG is that various propeller speeds can be selected during maneuvering conditions when the gas turbine is at idle. This capability is achieved by partially inserting the reversing vanes in the hydraulic fluid filled coupling during low rpm conditions. The RRG has a maneuvering efficiency of about 80% with the system acting as a normal hydraulic coupling, and less than 50% when the vanes are inserted for astern operation. System ancillary equipment includes a hydraulic pump, oil cooler, a fully-automatic "freewheeling" overrunning clutch, and a controls system. The RRG system adds about 20% to the gear weight and 40% to the gear length but there are advantages over the CRP propeller arrangement:

- Unit construction provides easier maintenance and increased survivability
- Lighter propeller, shafting, and appendages result in
  Lower cruise horsepower
  Reduced fuel for equal ship endurance
  Slightly increased maximum speed
  Lower annual fuel usage
  Smaller wakes

• Lower ship acquisition and life cycle costs

Testing of the RRG is currently underway on the FFG-7 Class propulsion plant at the Naval Ship Systems Engineering Station (NAVSSES) land-based test facility. Around the end of this decade, the Navy may conduct at-sea tests of the RRG to support planned installations of the system on the AOE-6.

Electric Drive

Flexibility in machinery arrangements and in system operation have been long recognized attributes of *Electric Drive Systems*. Such systems, which incorporate prime mover driven generators powering direct coupled or geared reversible propulsion motors would be particularly attractive in multiple shaft ships with many, or widely separated engines, or in advanced crafts, such as SWATH's, where several sets of (right angle) bevel gearing would otherwise be necessary. The ease with which electric systems can be reconfigured with switch gear could enhance survivability. Cross connection at cruise power levels (e.g. one engine powering two shafts), together with speed ratio control, can additionally permit propulsion engines to be operated at favorable load and speed conditions, an especially desirable feature with simple cycle gas turbines with poor part power fuel economy. Offsetting these desirable features of electric transmissions has been their higher cost, lower transmission efficiency and greater weight and volume compared to mechanical drives.

During the last two decades there has been a number of technology advances which are being exploited to improve the relative attractiveness of electric transmissions. The most important of these in the near term is development of solid state adjustable frequency ac power converters with capacities in the tens of megawatts and the widespread use of direct liquid cooling to reduce the size and weight of motors and generators.[35] (The power density improvement possible with direct liquid cooling, first in the machine stator and secondly in both rotor and stator, is illustrated in Fig. 65 for a large propulsion motor.) These industrially based technologies are central to the Navy's current advanced development program, which is targeted at demonstrating full scale alternating current (ac) drive equipment in the early 1990's. Figure 66 schematically illustrates two machinery options which could be made available in such a system, propulsion derived ship service (which is discussed elsewhere in this paper) and high speed motors geared down to propeller rpm. The gearbox, which would likely be epicyclic, permits reduced motor diameter with some penalty in the package efficiency and length. It also opens up the opportunity of selecting a contrarotating output. The frequency changer, which will be relatively large, but light in weight, provides for variable speed ratio as well as rotor reversal.

Direct current (dc) electric ship drives are at an earlier stage of development than ac machinery.[36] The current Exploratory Development Program is advancing the technologies of superconductive excitation, compact (solid or liquid metal) current collection and direct conductor liquid cooling. Applied separately or in combination, these technologies are expected to provide dc motors and generators which are smaller, more efficient, and easier to control than their ac counterparts. To illustrate, projected motor power density is compared in Fig. 67. Direct current system options,

shown schematically in Fig. 68, are expected to demonstrate efficiencies approaching 95% compared to 90% for ac drives.

The approach to building a technically sound base for full scale dc drive development began with construction of 300 kilowatt proof-of-principle electrical machines and experimental design of full-scale 23-37 megawatt systems. Figures 69 and 70 show 300 kW acyclic dc machinery incorporating liquid helium cooled superconductive field windings and liquid metal brushes built under this program. After landbased evaluation, the 300 kilowatt system work progressed to a successful shipboard demonstration in the DTNSRDC 20-meter testcraft, JUPITER II, which took place in September 1980. The JUPITER machinery arrangement is shown in Fig. 71.

The 300 kW work was followed by development of 3,000 hp "model" machinery incorporating materials fabrication techniques and stress levels defined in full scale designs. Designs incorporating both superconductive and normally excited equipment were built. The rectified alternator of Fig. 72 is one example of high power density achievable at generator speeds without cryogenics.

Advanced design ancillary components for dc propulsion systems such as lightweight switch gear, liquid cooled coaxial transmission lines and closed cycle helium refrigerators have been included in the 300 and 2,250 kW programs. Cryogenic refrigeration equipment development in support of superconductive motor and generator development is concerned with the two major components of such systems, compressors and liquefiers. Alternative design concepts for each of these components are being developed in experimental prototype models. Unlike the scale-modeling effort in electrical machines, the helium refrigeration equipment is being developed at full-scale, i.e., the helium compressors and liquefiers under development are sized to provide cryogenic helium for the superconductive magnet in a full scale propulsion motor or generator. One such system is illustrated in Fig. 73.

Current work includes continuing limited operations of 2250 kW system hardware, feasibility evaluation of critical technologies and new design options in 2250 kW host machines, examination of contrarotating motor designs, and continued technology development in brush and magnet systems. If a successful high current, high field wire can be developed from the recently discovered higher temperature superconductors, the relative attractiveness of dc drives should be significantly increased.

Contrarotating Transmissions

Monohull combatants can be unnecessarily large and expensive when compared to alternative hull forms designed to cope with emerging fleet requirements. One example is the small waterplane area, twin hull ship (SWATH) designed for superior seakeeping in high sea-state conditions. As shown in Fig. 74, the low volume, strut-pod arrangement of this hull form places new demands on the power drive train. Two machinery design options have emerged as candidates for the unique requirements of SWATH propulsion; electric drive (discussed in the previous section) and contrarotating (C/R) propellers. Compared to fixed pitch (FP) propellers, C/R SWATH propulsion model studies[37,38] have shown higher efficiency, resulting in reductions of over 10% in power and fuel requirements for fixed mission endurance. Unfortunately, these gains are achieved at the expense of a more complex shafting system as depicted in Fig. 75.

Since the early 1960's, C/R propulsion has been used on two Navy ships, the submarine USS JACK (SSN 605), and the USS ALBACORE (AGS 569). After initial thrust bearing design and lubrication problems were resolved, the shaft systems continue to operate successfully without major problems[39,40]. Since these earlier designs, new materials and design techniques have evolved which should reduce the traditional weight and volume penalty of C/R systems. Based on past operating experience and new hull form requirements, future design trends are projected:

1. System reliability and maintainability will be a paramount design priority owing to the systems increased complexity and remote location in the ship. For low volume hull forms, a modular design approach should facilitate maintenance and reduce MTTR.
2. The need for low acoustical and magnetic signatures will encourage increased use of shaft line isolation techniques and nonmetallic materials.
3. System weight and volume penalties will be significantly reduced with the application of lightweight composite shaft sections. These fiber reinforced resin materials are immune to seawater induced corrosion and shaft line currents which govern the fatigue limit, weight and size of metal shafts. In addition, composite materials are more flexible and will facilitate installation and alignments.

   Except for applications where C/R motors can be used, epicyclic gears will be the uncontested choice for speed reduction between a single rotating power source and the C/R propeller. Compared to conventional locked-train gears of equal load carrying capacity, epicyclic gears are inherently smaller and can readily be designed to convert single-rotation in the first stage into a C/R output. A fully C/R arrangement (called simple bicoupled)[41] where torque is shared between shafts allows better isolation of gear meshing vibrations from the gear housing/foundation[42] (Fig. 76). Possible arrangements of direct coupled contrarotating motor drives are illustrated in Fig. 77.[43]

Composite Shafting

Over the past two decades, fiber reinforced epoxy (composites) technology have been extensively developed by the aerospace industry and used in drive shafts for both military and commercial vehicles.[43] Over the past five years, the US Navy has used this technology to develop ship main propulsion drive shafts for reduced machinery acoustic/non-acoustic signatures, weight, and life-cycle cost. Conventional Navy steel shafts suffer from both galvanic or localized corrosion which must be inhibited by costly coating or wrapping techniques (i.e., paint, rubber, or GRP wrapping). Periodically, shaft removal and replacement is necessary when deterioration progesses unchecked. For class II steels, the size and diameter of a metal shaft are dictated by the relatively low allowable fatigue limit (approximately 6,000 psi)[44] in the seawater environment. As metal shaft size increases, so does weight, cost, and alignment and installation problems. Compared to steel shafts, fiber reinforced composite shafts are projected[45] to have several benefits for ship main propulsion applications:

- Outside diameter is reduced up to 10%. Overall ship impact will be more significant since associated bearings, couplings, seals, and joints will be smaller.

- Shaft weight is decreased more than 50%, with corresponding reductions in bearings and couplings.
- Vibration and noise damping improve significantly, which could eliminate or reduce future needs for shaft line vibration reducers and sound isolation couplings.
- Deleterous shaft corrosion currents (associated with galvanic potentials between the hull and propeller) will be significantly reduced due to the almost zero conductivity of the composite shaft. Likewise, magnetic signatures associated with the shaft will be almost eliminated.
- Shaft acquisition cost will be reduced approximately 25% based on recent price trends of composite materials.
- Overall life cycle cost will be lower as a result of lower maintenance and increased life of bearings and seals. This is credited to the increased flexibility of composites. (Bending modulus of composites is ten times lower than that of steel.)
- Increasing the consumption of composite materials (fibers and resins) for commercial and military applications will reduce our reliance on imported alloying metals.
- Shaft damage tolerance increases significantly under impact loading[46] e.g., as experienced when propulsion appendages impact ice or other massive objects.

As with any new application, this technology brings a few unsettled technical issues when considered in the context of shipboard requirements. To answer these issues, current Navy R&D programs are focusing on three areas of development:

1. Composite shafting for ship propulsion requires thicker laminates than encountered in most commercial or other military applications. As a result, improved processing, quality control, and inspection standards are needed to insure flaw free shaft sections. New methods of nondestructive testing and evaluation are being explored within the Navy and private enterprise.[47]
2. Inboard composite shafting will require a fire safe protective shield or coating to control flammability, smoke, and toxicity. Intumescent paint which forms an insulating char may be one answer to combating this threat.
3. Early Navy tests indicate that the coupling between the composite and metal-end flange is the weakest location under static and cyclic stress conditions. Both analytical and experimental tests are underway to identify optimum geometry and attachment of the joint.

Initial testing of composite shafting was conducted in the early 1980's aboard an 80 foot yard patrol vessel (Fig. 78). After three years and 3,000 hours of testing under all possible maneuvering conditions, including crashback operations, the composite shaft has shown no degradation of strength or materials characteristics in the seawater environment.[45,48] Based on these encouraging results, a large diameter (33 inch OD), 33 foot section composite shaft has been designed for installation aboard the combatant support ship USS SACRAMENTO (AOE-1 Class). Initial shipboard tests are planned for 1989 at full rated loads up to 50,000 shp and 140 rpm. Laboratory tests prior to and following ship trials will identify any change in material characteristics. Successful completion of these tests, in concert with investigations into flame retardancy and nondestructive evaluation, will provide data for developing a Navy standard composite shaft design.

EPILOGUE

Although this paper attempted to "survey" current ship machinery R&D activities, all relevant developments could not be included in a document of this length. We hope, however, that readers are left with some appreciation of the extent and depth of development programs now in the "system."

Machinery is an essential, and in many cases, the predominant factor in providing the technology lead now enjoyed by the U.S. Navy. To assure this lead is sustained in an era of limited resources will compel the identification and selection of development candidates which are responsive to the "need" and offer the highest possible payoff to risk ratios. Resultant R&D programs must be timely and economic with reliable, supportable products. These are the challenges to the machinery development community. Machinery users are equally challenged to actively consider and exploit new machinery along with the innovative ship design opportunities and improved operational characteristics that advanced technology makes possible. Working together, machinery developers and users can help assure that the Navy's future surface forces are simultaneously more capable and affordable.

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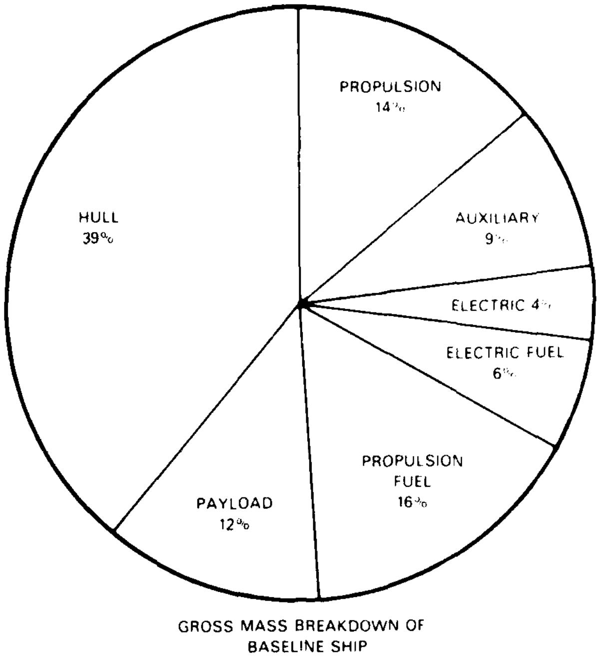


Fig. 1. Gross mass breakdown of DD 963 Class.

Fig. 2. Single screw compressor with cylindrical main rotor and planar gaterotor, Zimmern design.

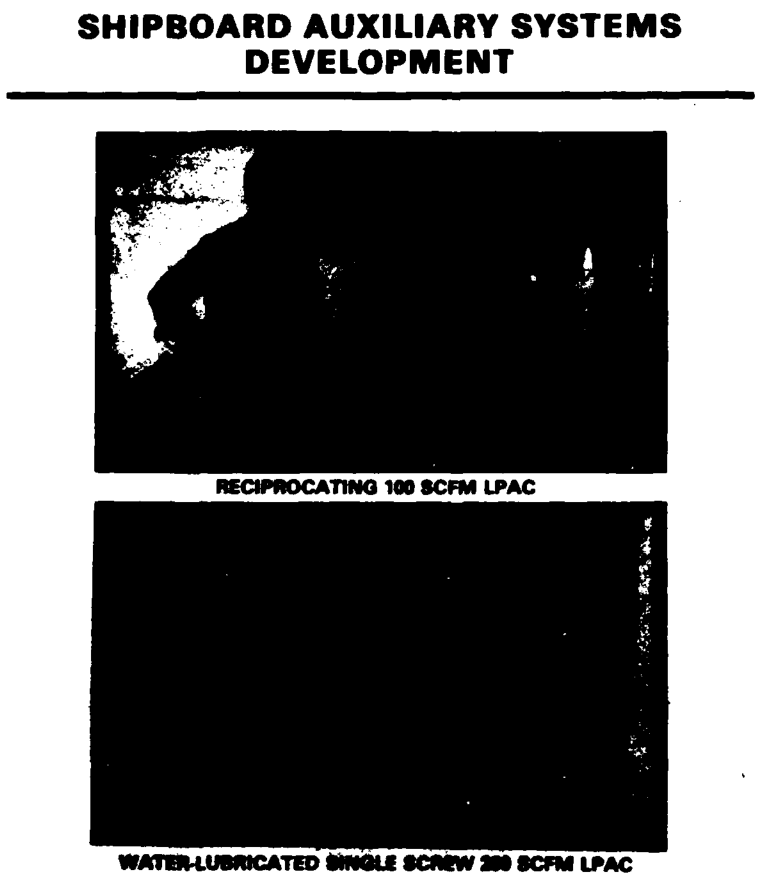


Fig. 3. Low pressure air compressor on USS SCOTT.

Fig. 4. Single screw air compressor.

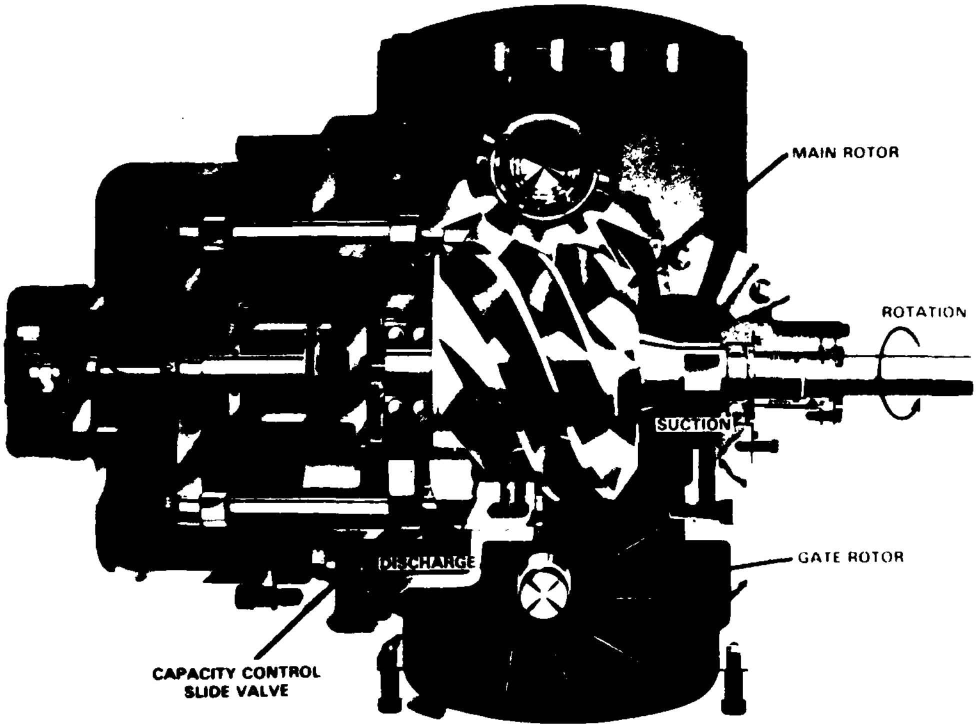


Fig. 5. Oil lubricated single screw refrigeration compressor.

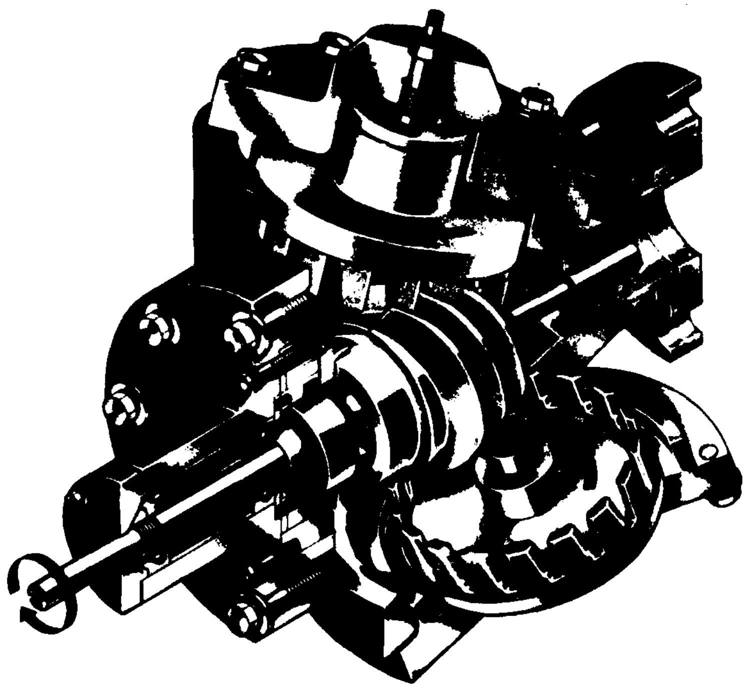


Fig. 6. Single screw oil service pump.

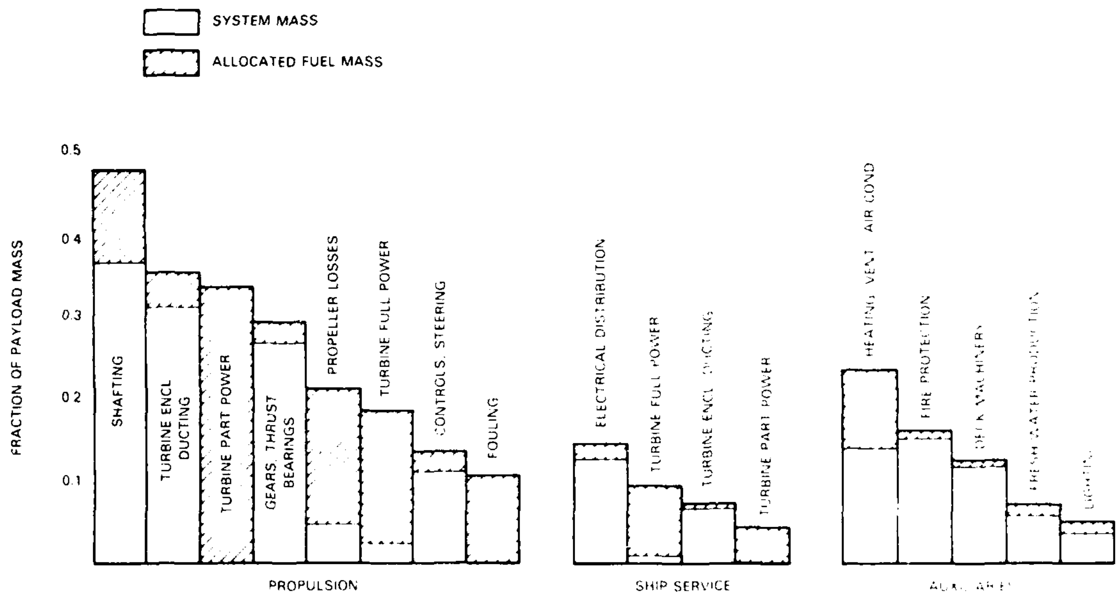


Fig. 7. Energy allocations.

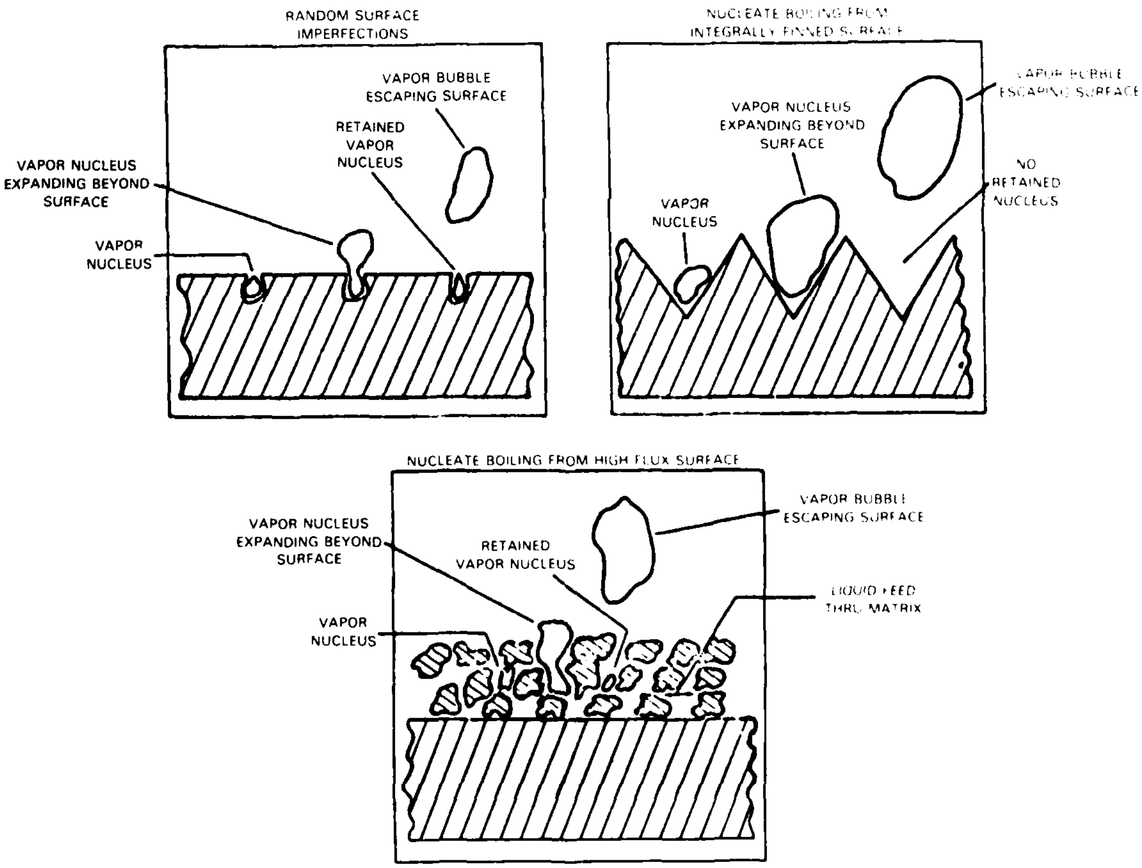


Fig. 8. Nucleate boiling.

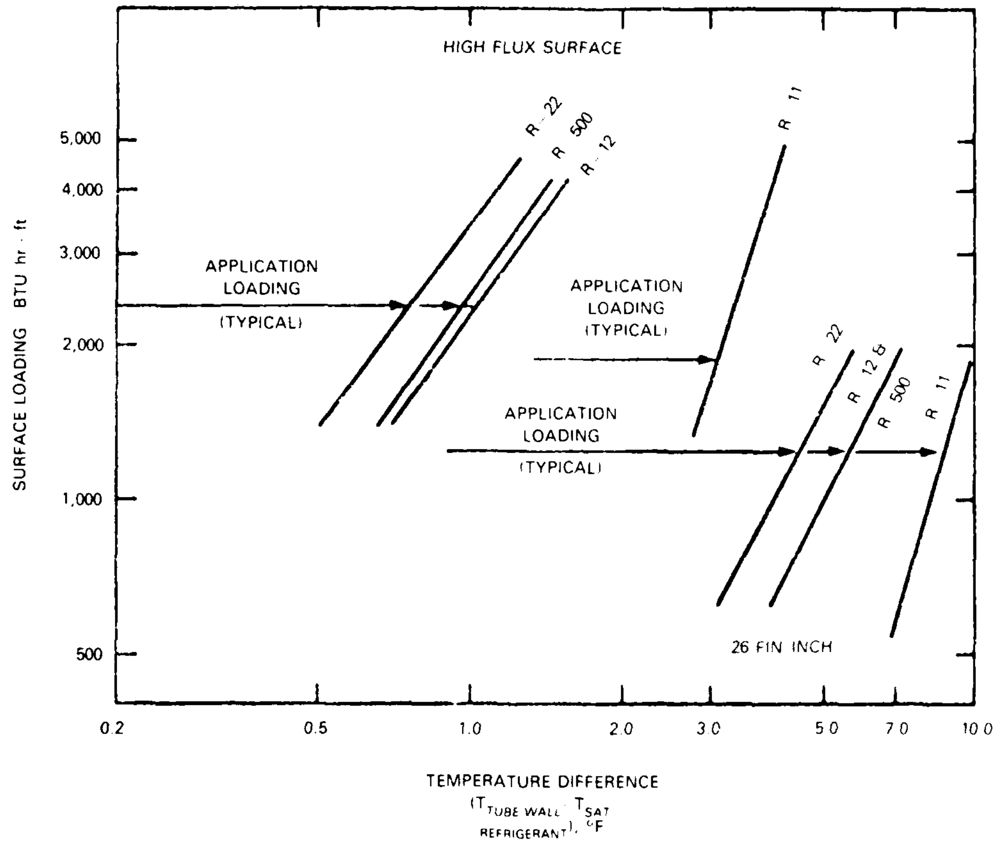
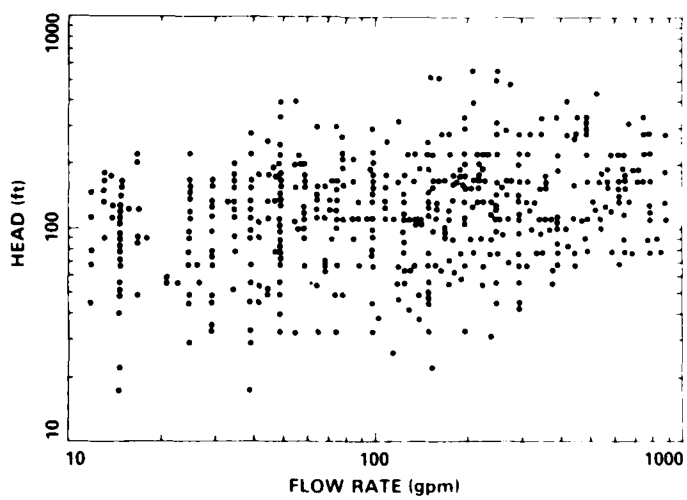


Fig. 9. High flux surface performance.



NUMBER OF PUMPS 29266 (2172 APLs, 470 PERFORMANCE REQUIREMENTS)
PUMP TYPE CENTRIFUGAL ONLY
APPLICATION ALL MAJOR FLUID SERVICES

Fig. 10. Surface combatant pump distribution.

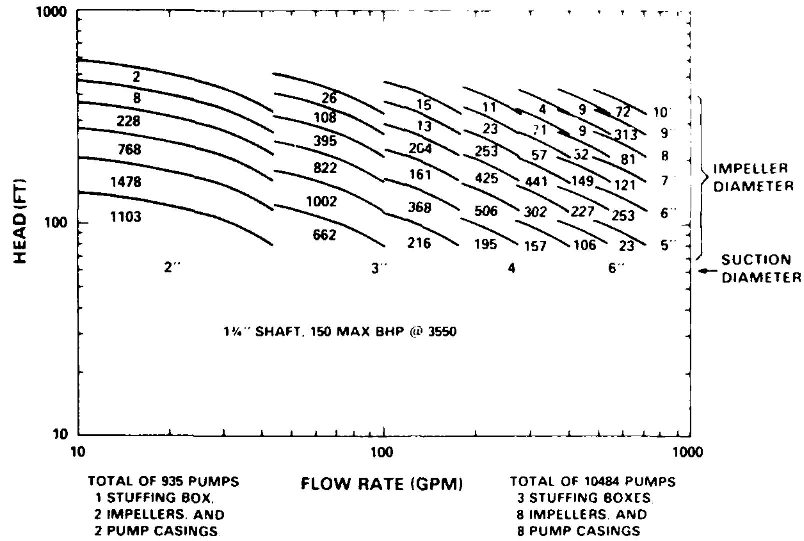


Fig. 11. Proposed future surface combatant standard pump families.

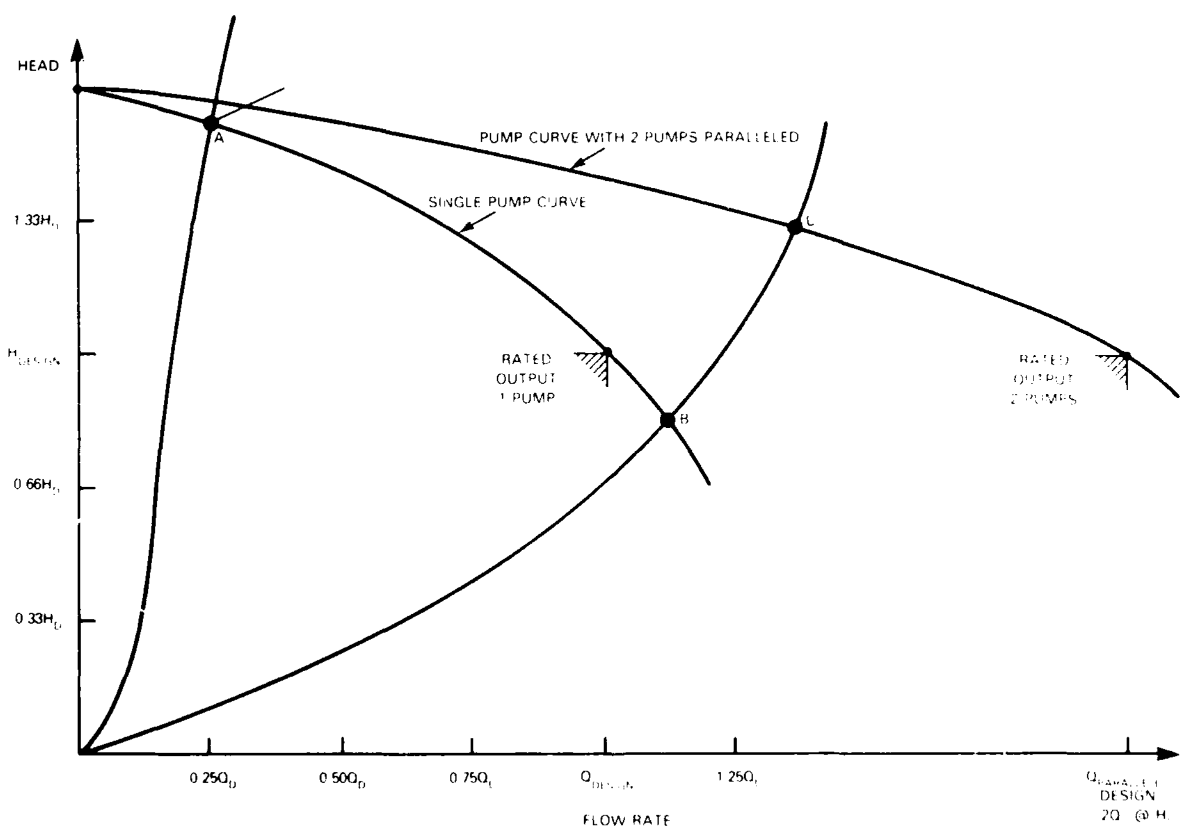


Fig. 12. Head capacity curves for typical fire main.

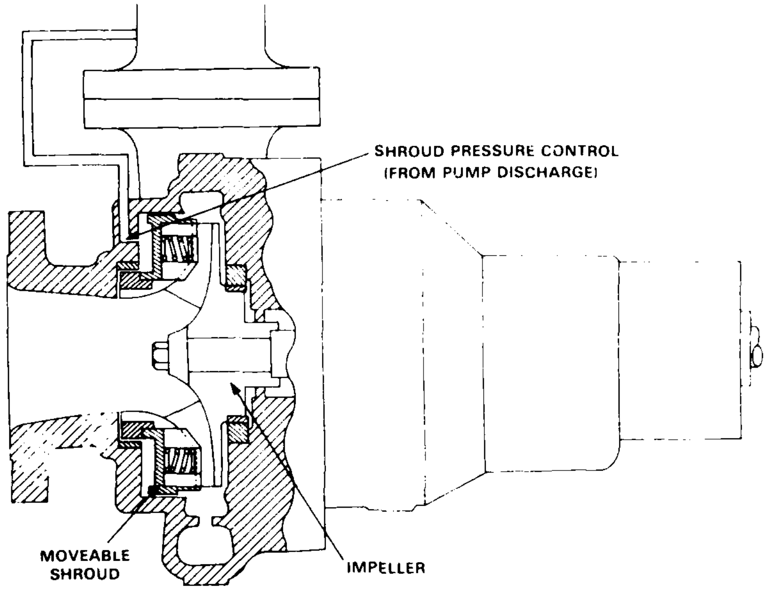


Fig. 13. Variable capacity centrifugal pump.

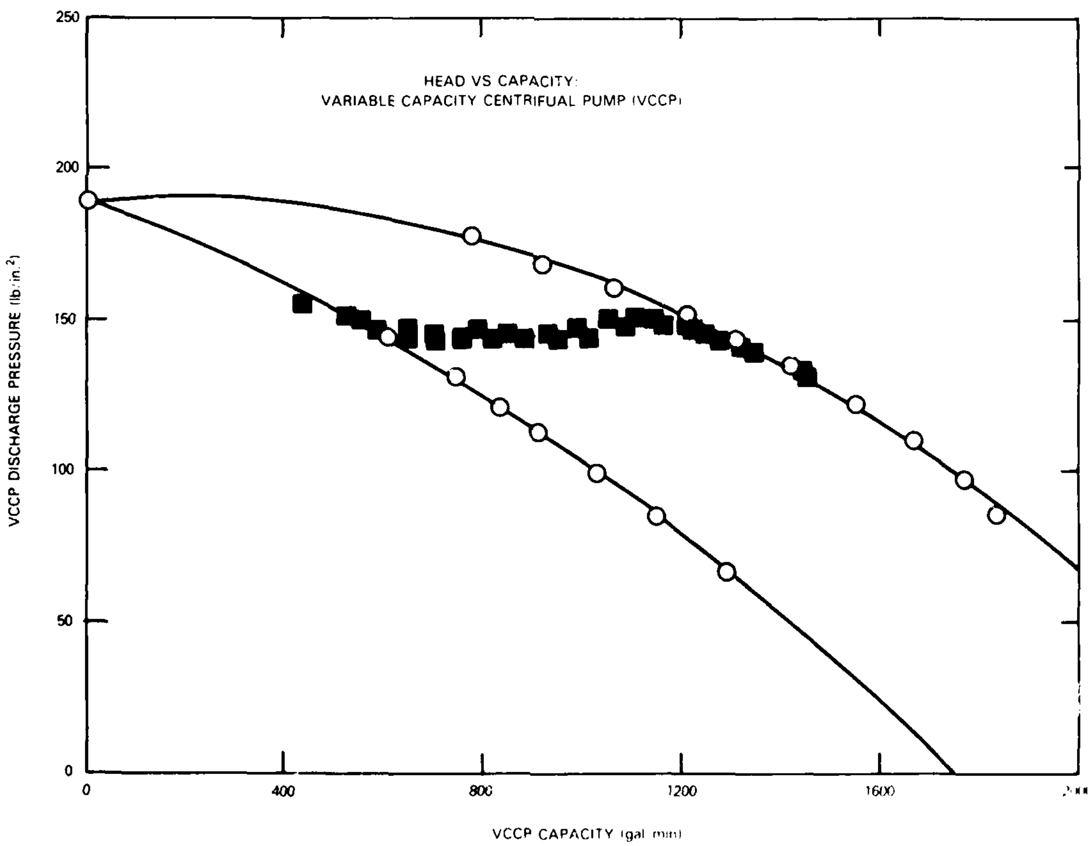


Fig. 14. Variable capacity centrifugal pump.

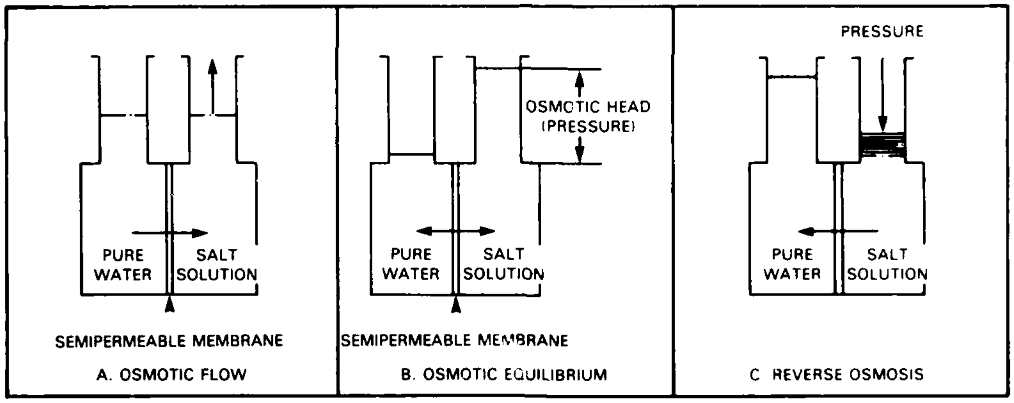


Fig. 15. Basics of reverse osmosis.

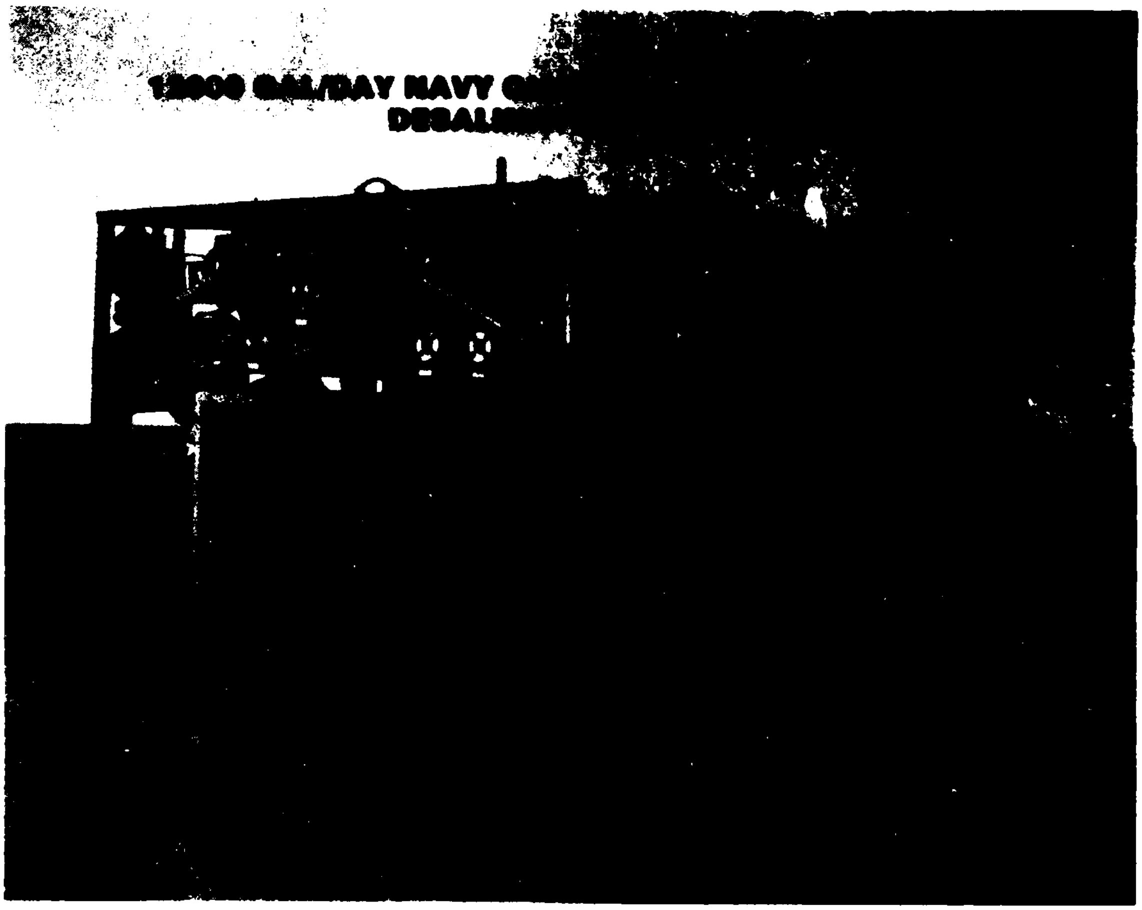


Fig. 16. Photo of production prototype undergoing landbased testing.

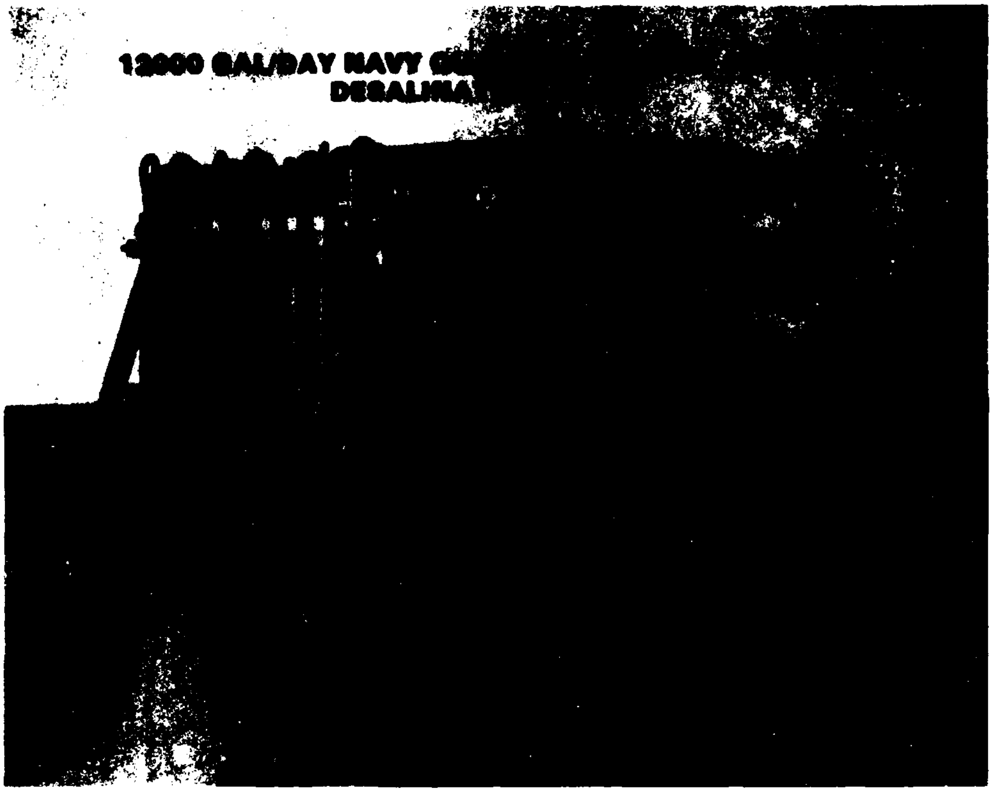


Fig. 17. Reverse osomsis desalinator.

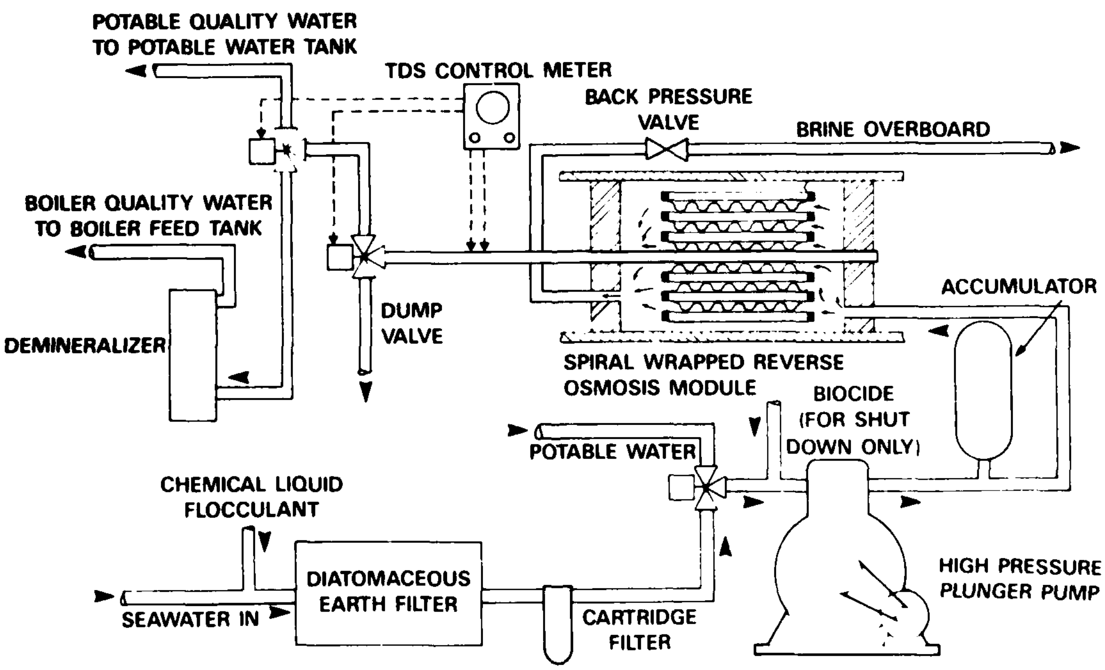


Fig. 18. Navy reverse osmosis desalination plant.

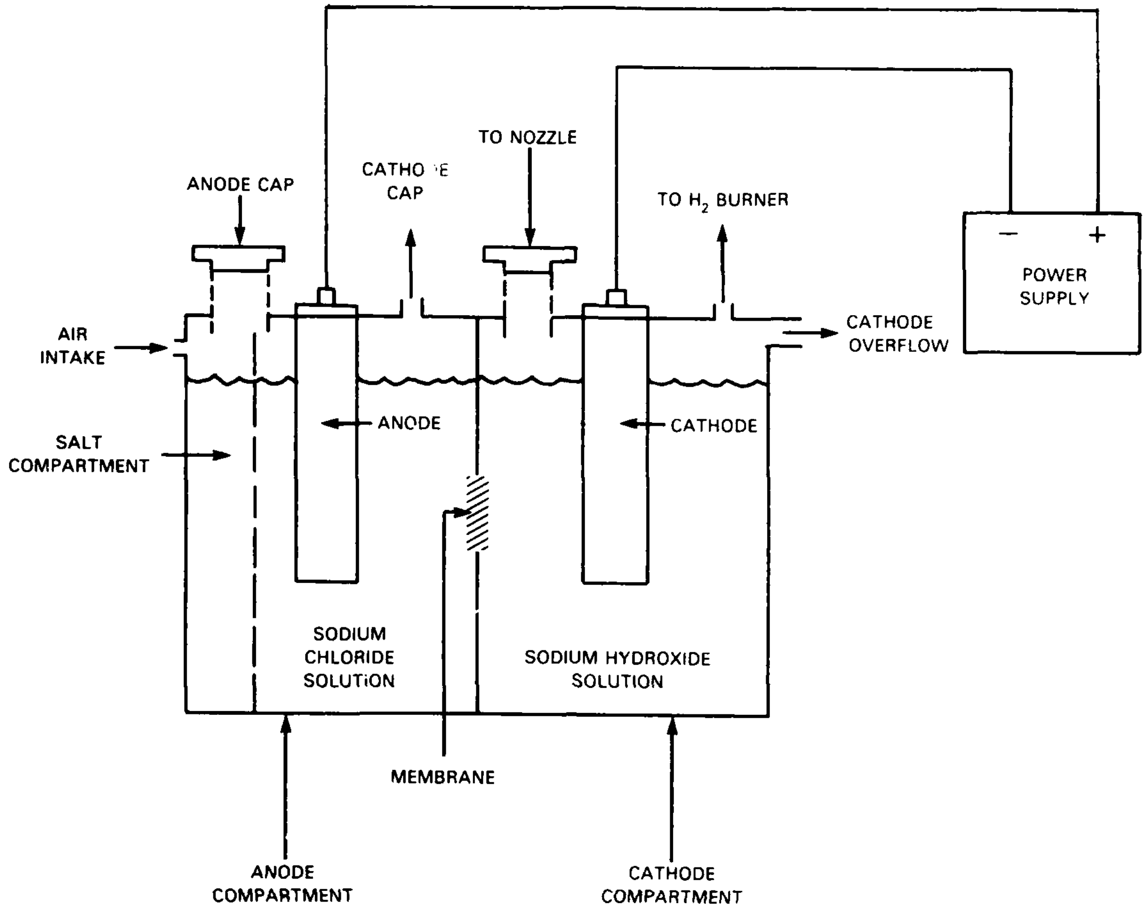


Fig. 19. Electrolyte chlorine generator.

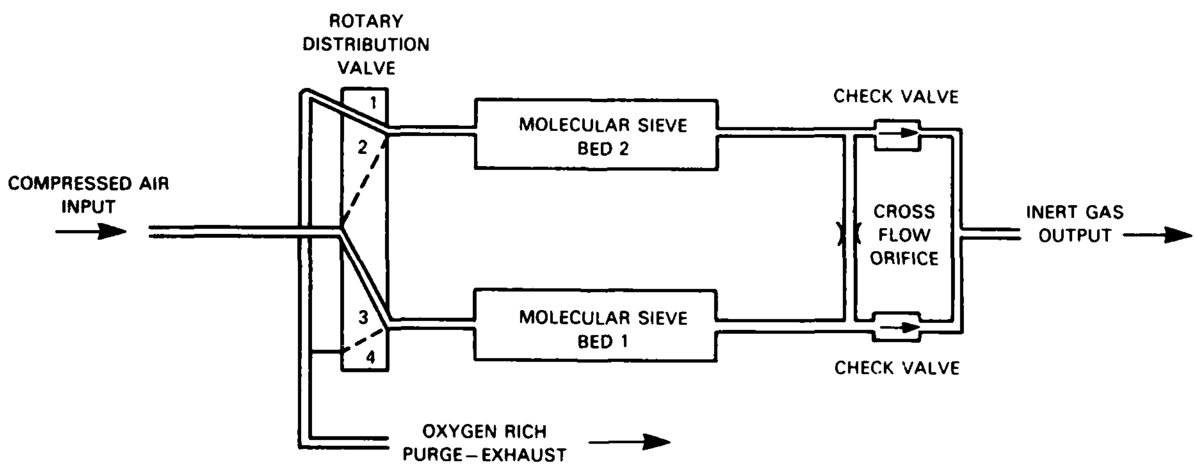


Fig. 20. Pressure swing molecular sieve nitrogen gas generator schematic.

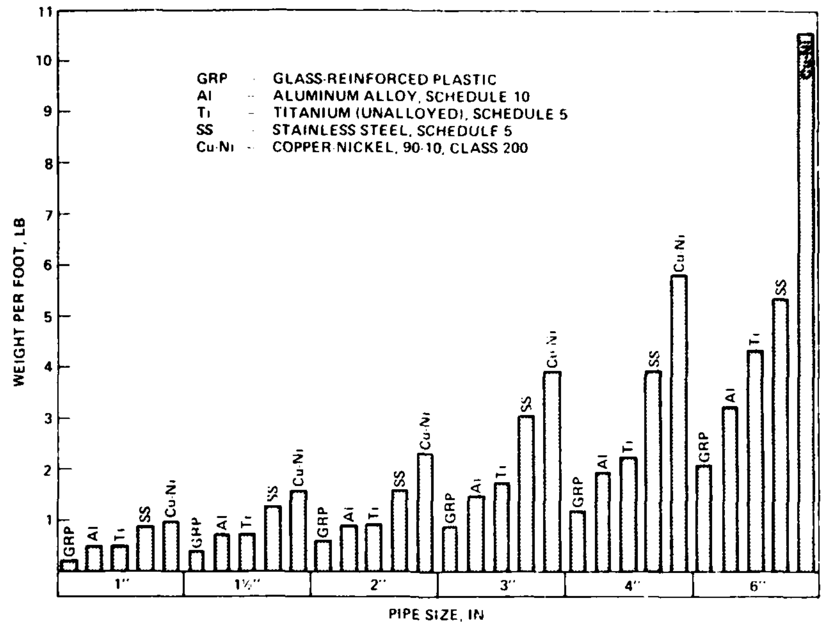


Fig. 21. Weight comparison of various piping materials.

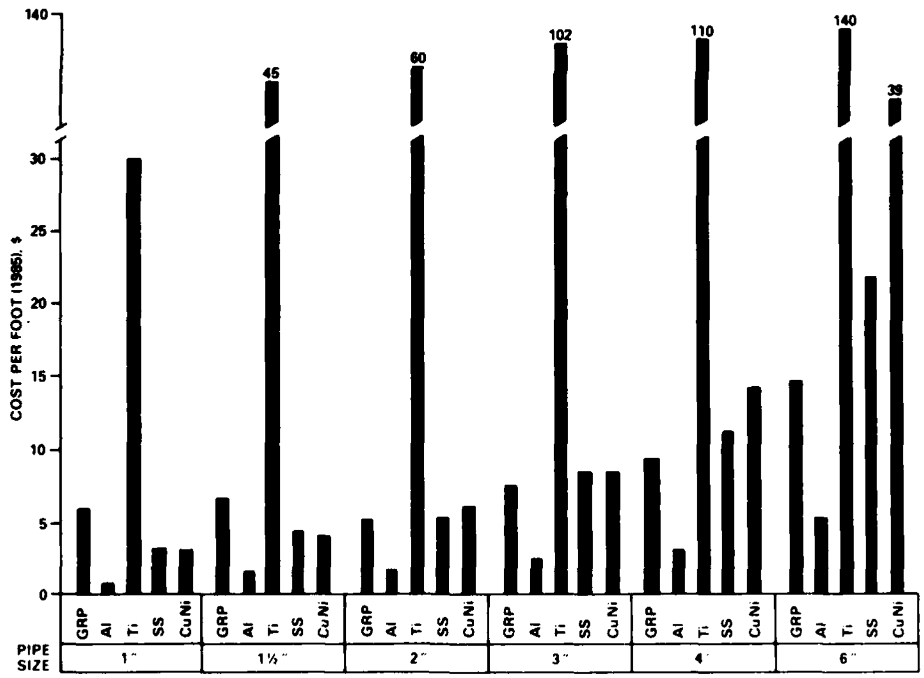


Fig. 22. Cost of piping materials.

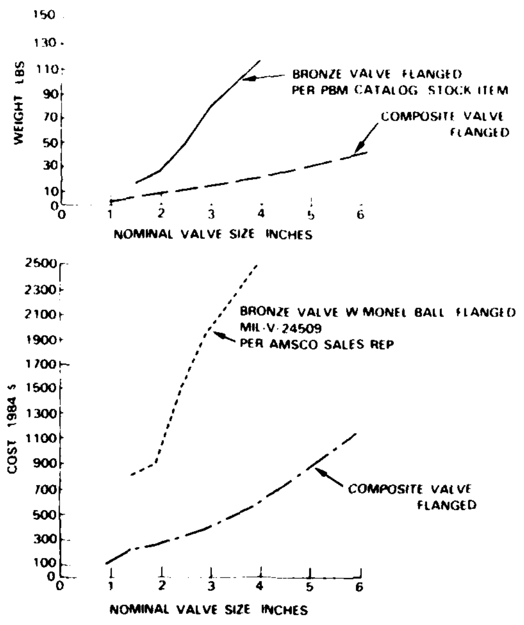


Fig. 23. Weight and cost comparisons for composite versus bronze ball valves.

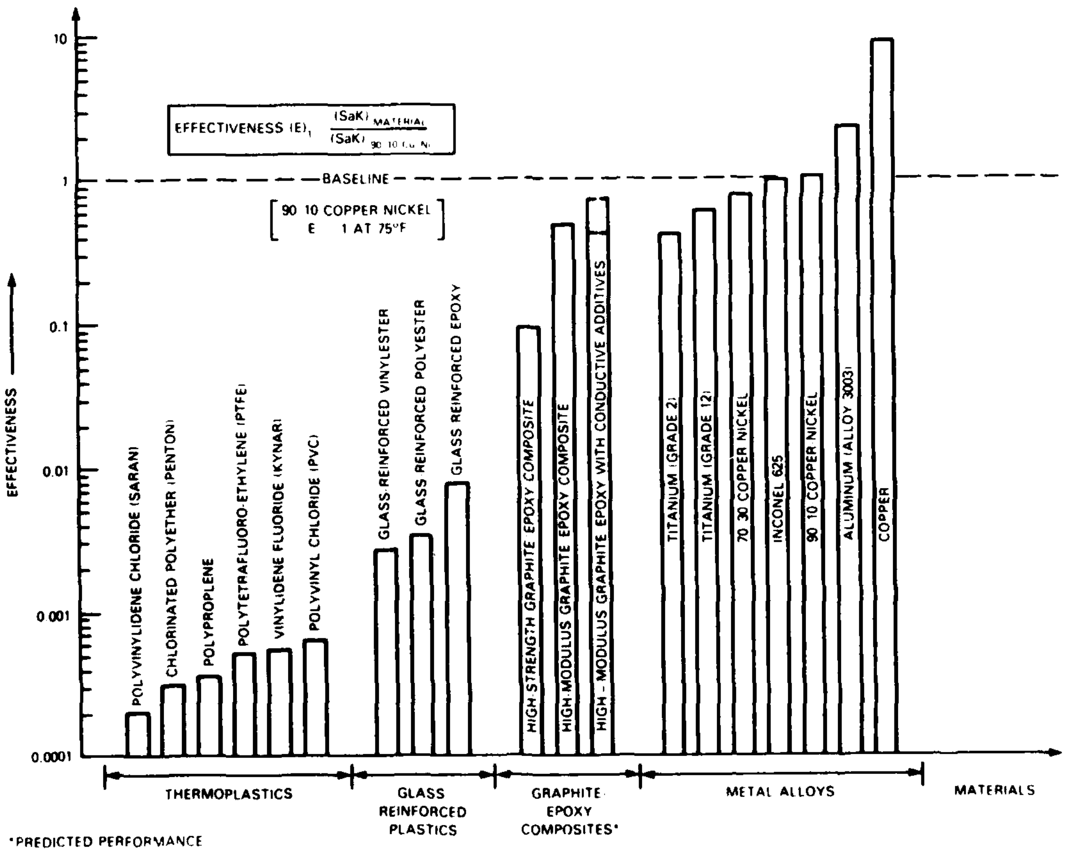


Fig. 24. Relative effectiveness of various materials as pressurized heat transfer tubes.

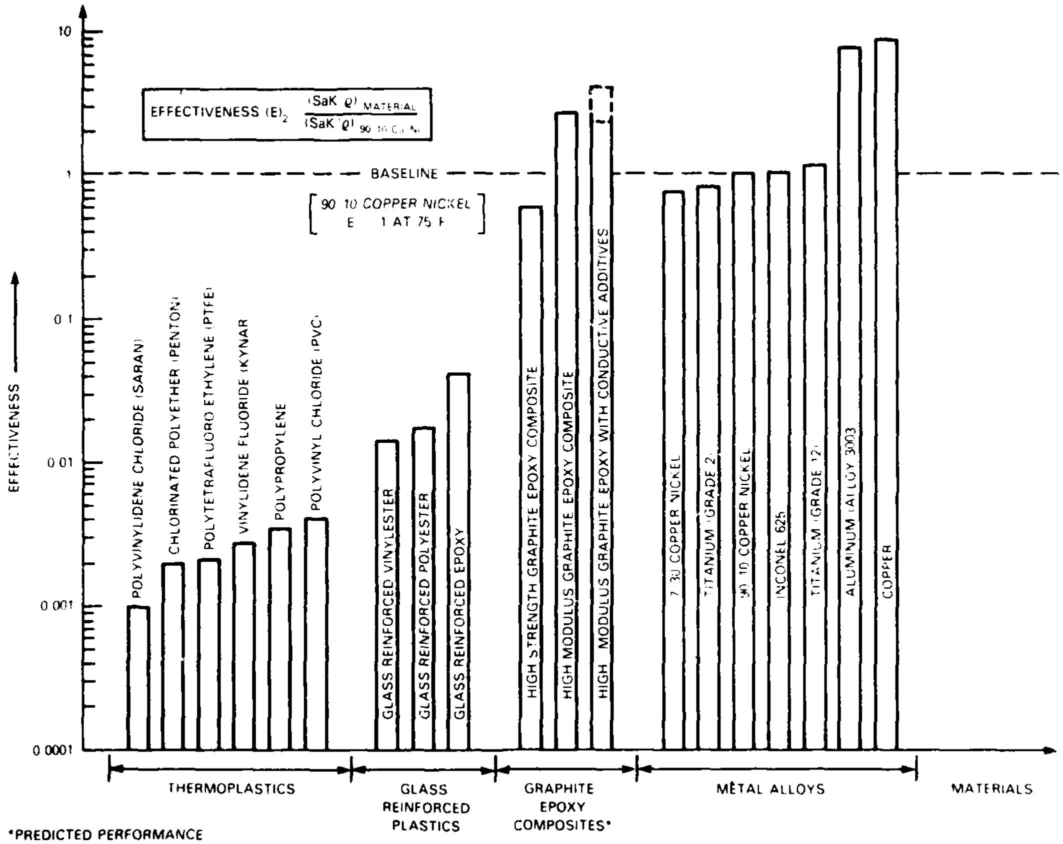


Fig. 25. Relative effectiveness of various materials as pressurized heat-transfer tubes.

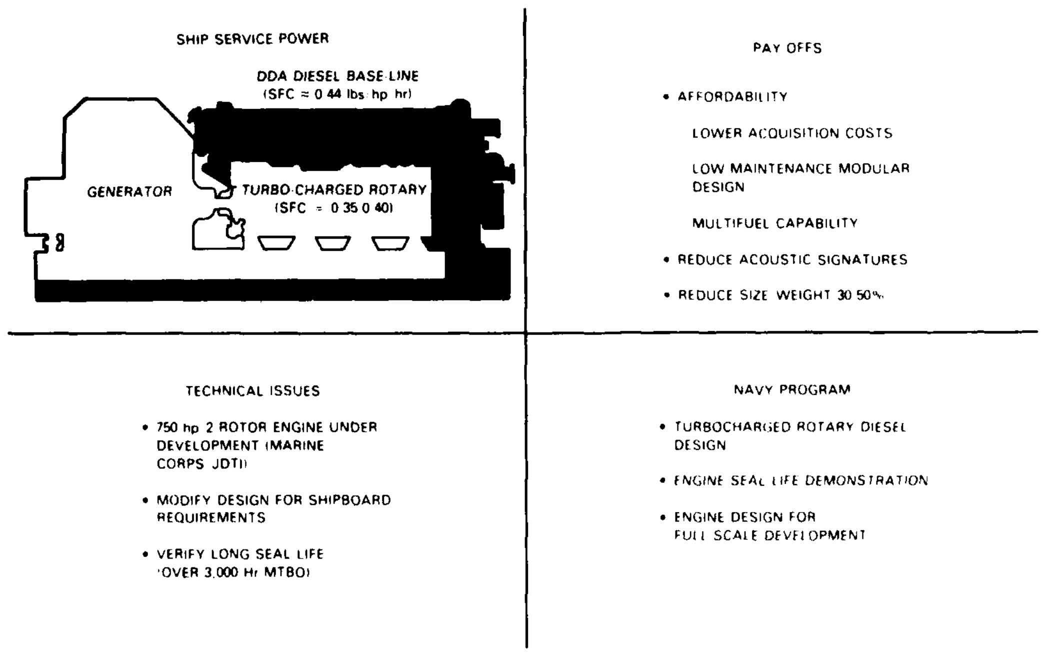


Fig. 26. Rotary engine for shipboard generator set.

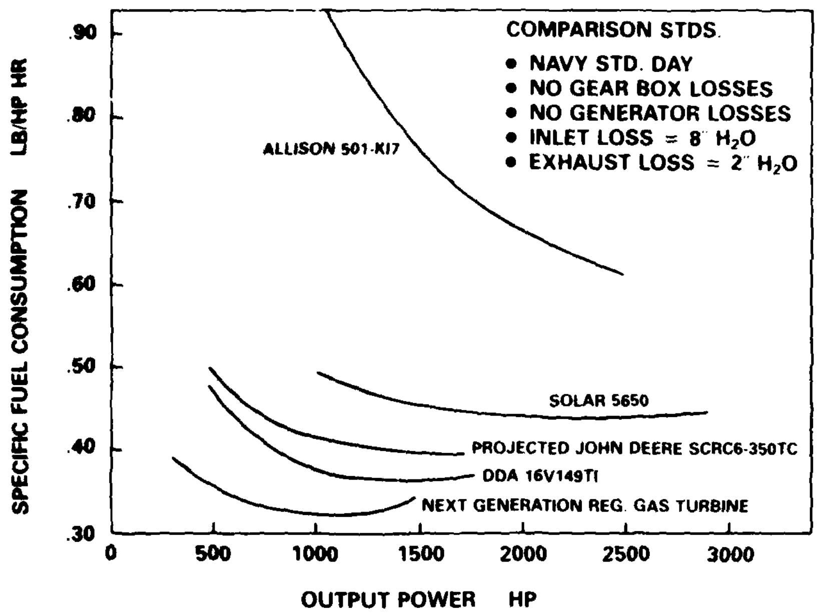


Fig. 27. Candidate ship service engines: low-mid power versus SFC.

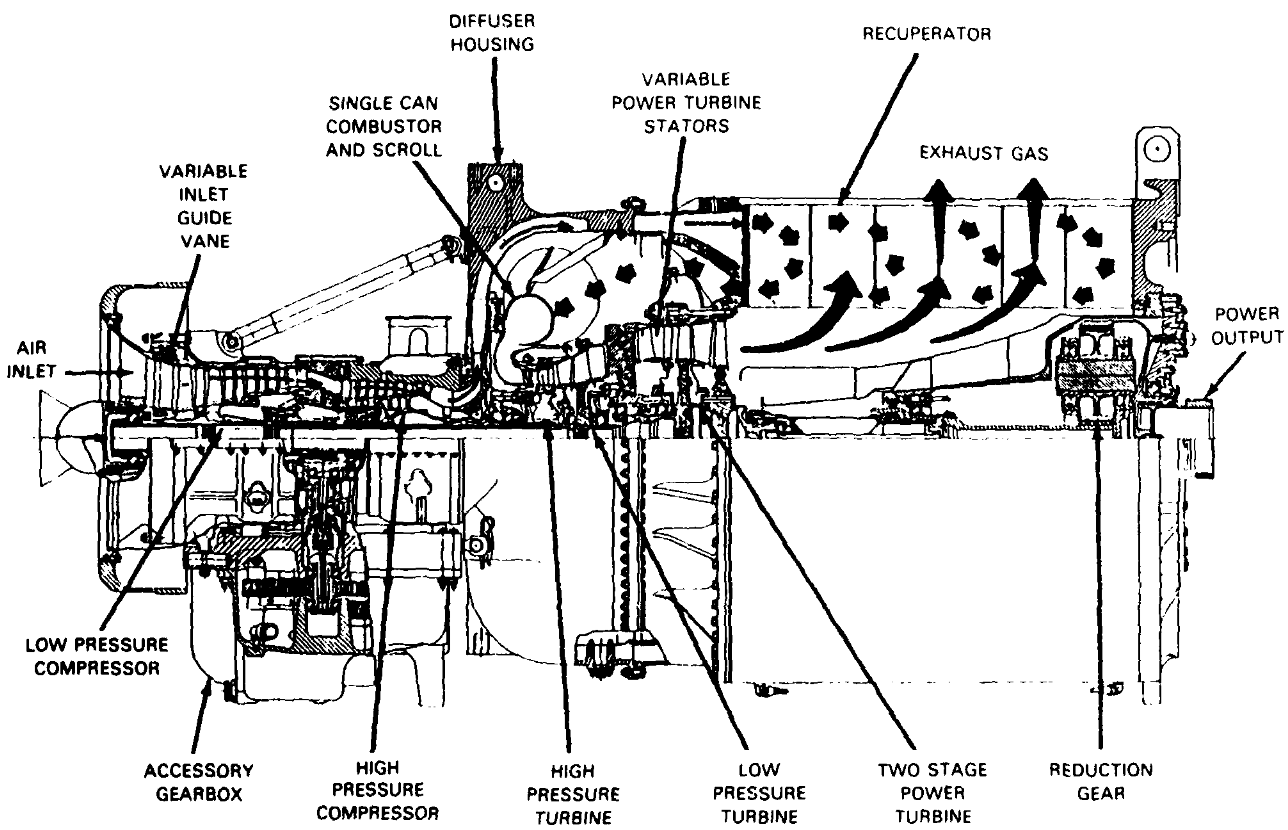


Fig. 28. Recuperated gas turbines for military vehicles (AVCO Lycoming AGT1500).

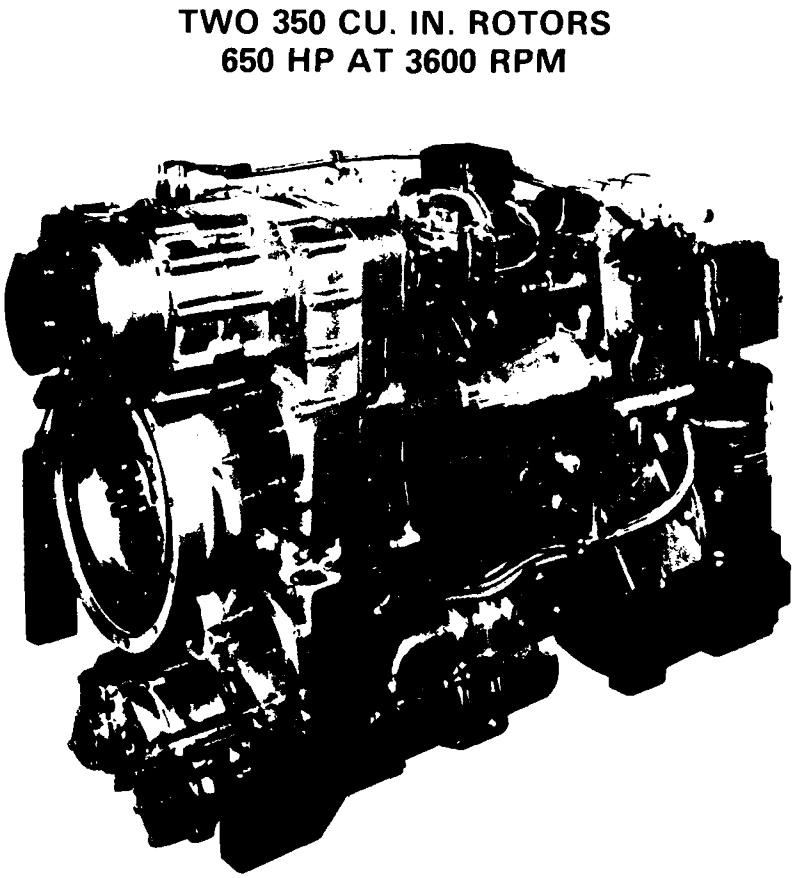


Fig. 29. Multifuel rotary engine.

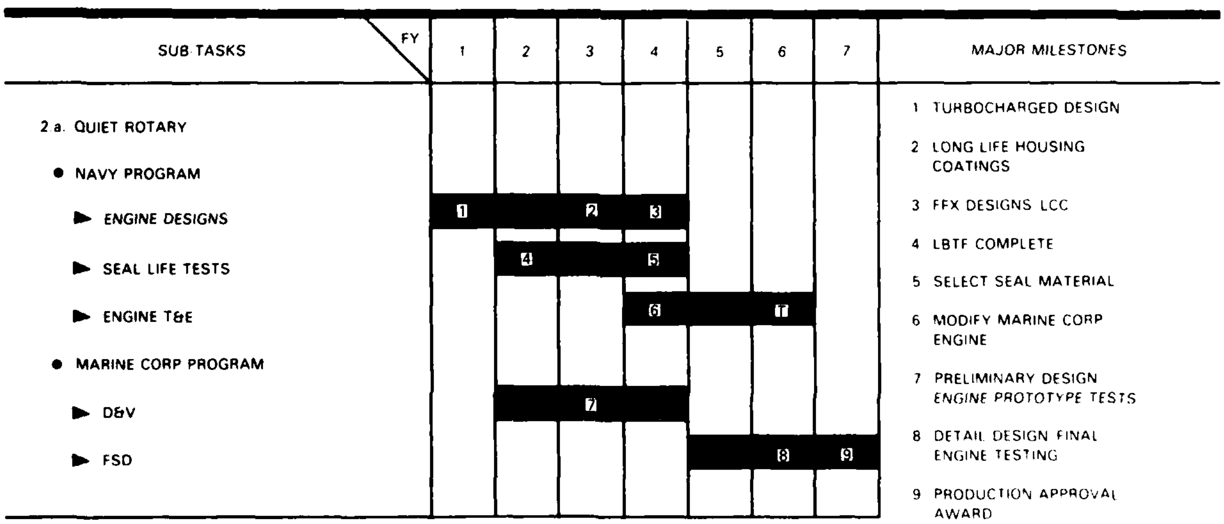


Fig. 30. Rotary engine development program.

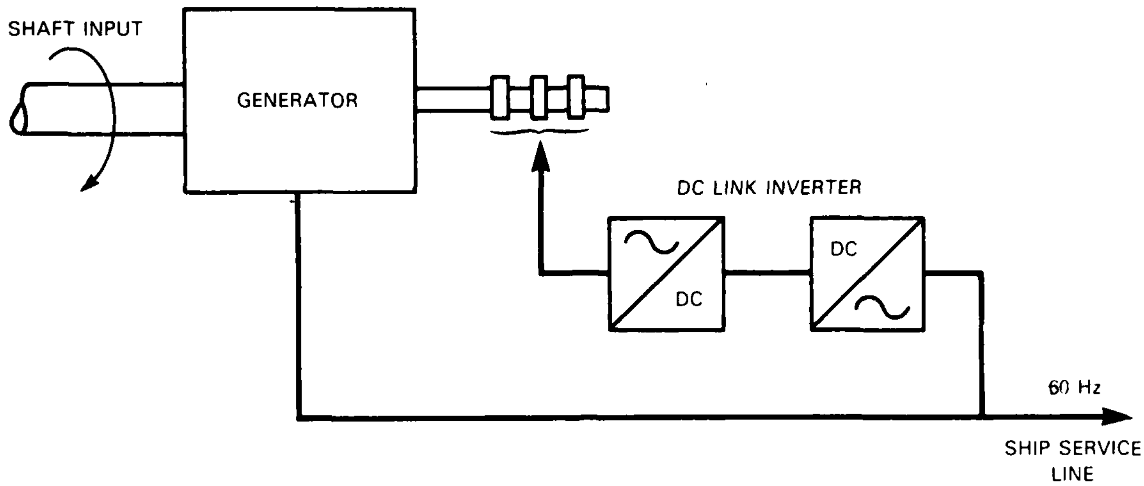


Fig. 31. Doubly fed VSCF generator.

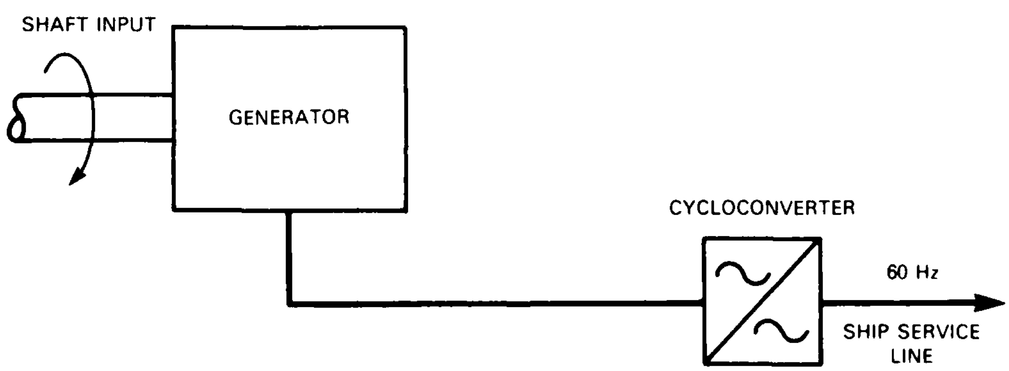


Fig. 32. Full power converter VSCF generator.

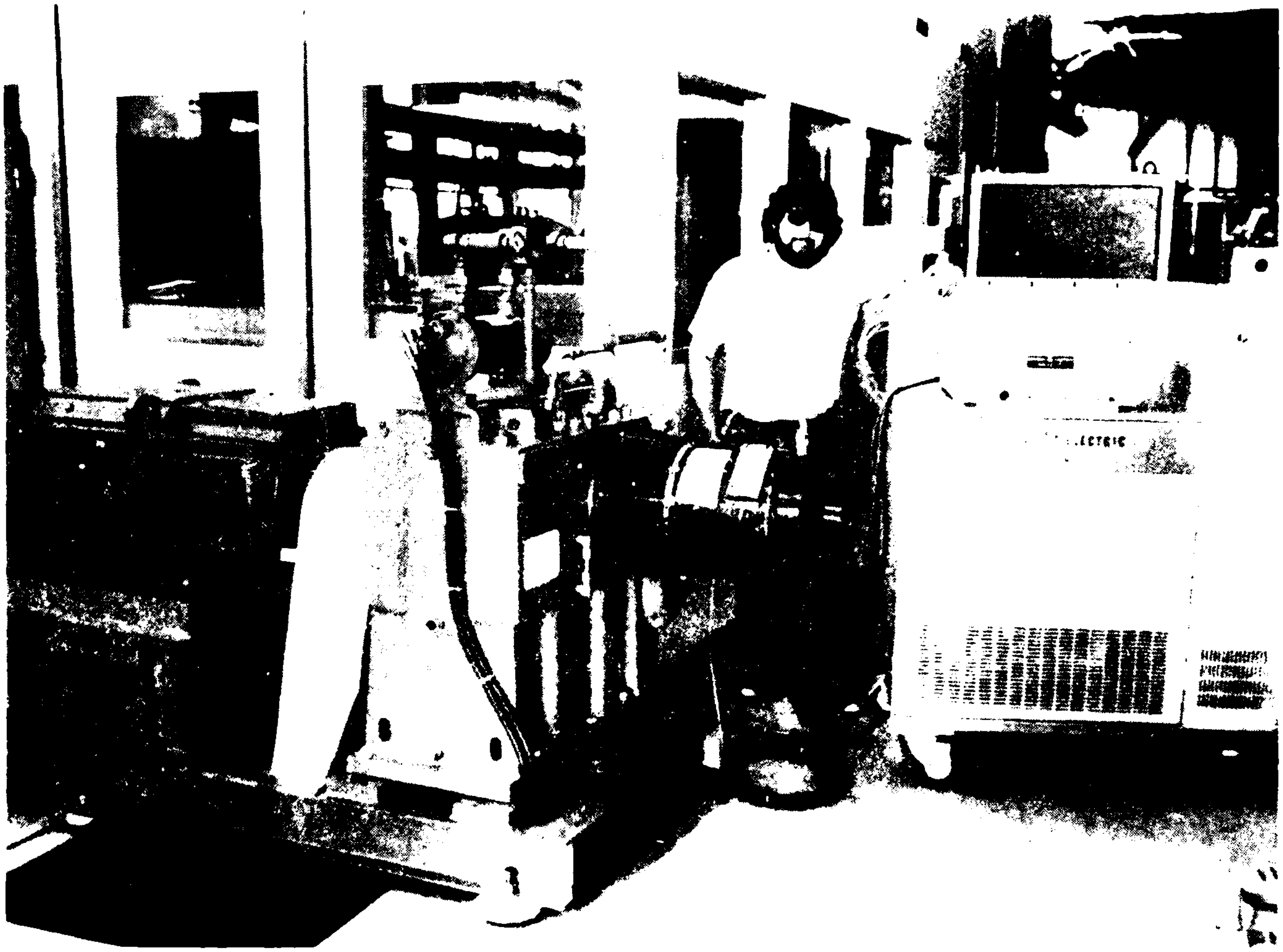


Fig. 33. 100 kW scale model with solid state conversion.

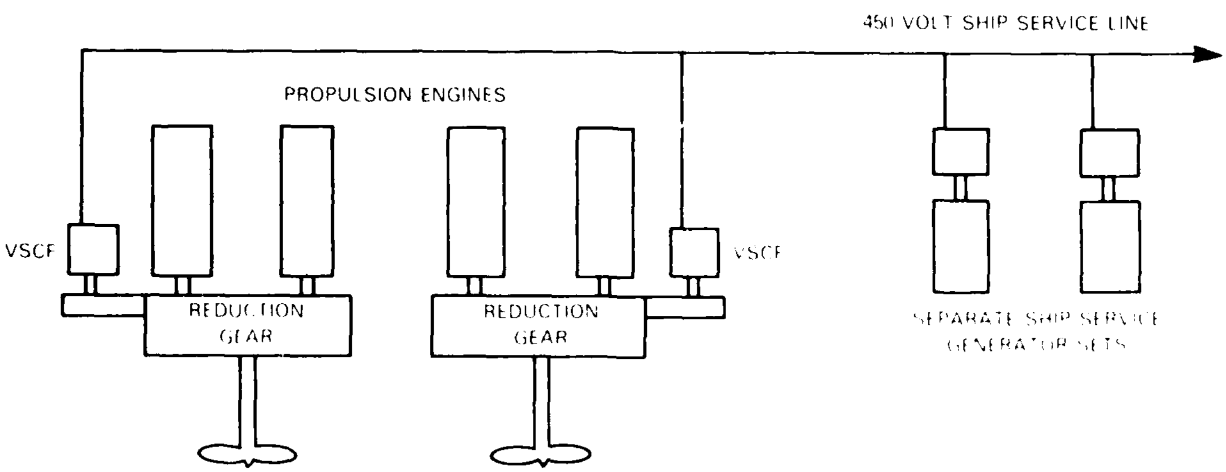


Fig. 34. Candidate PDSS configuration.

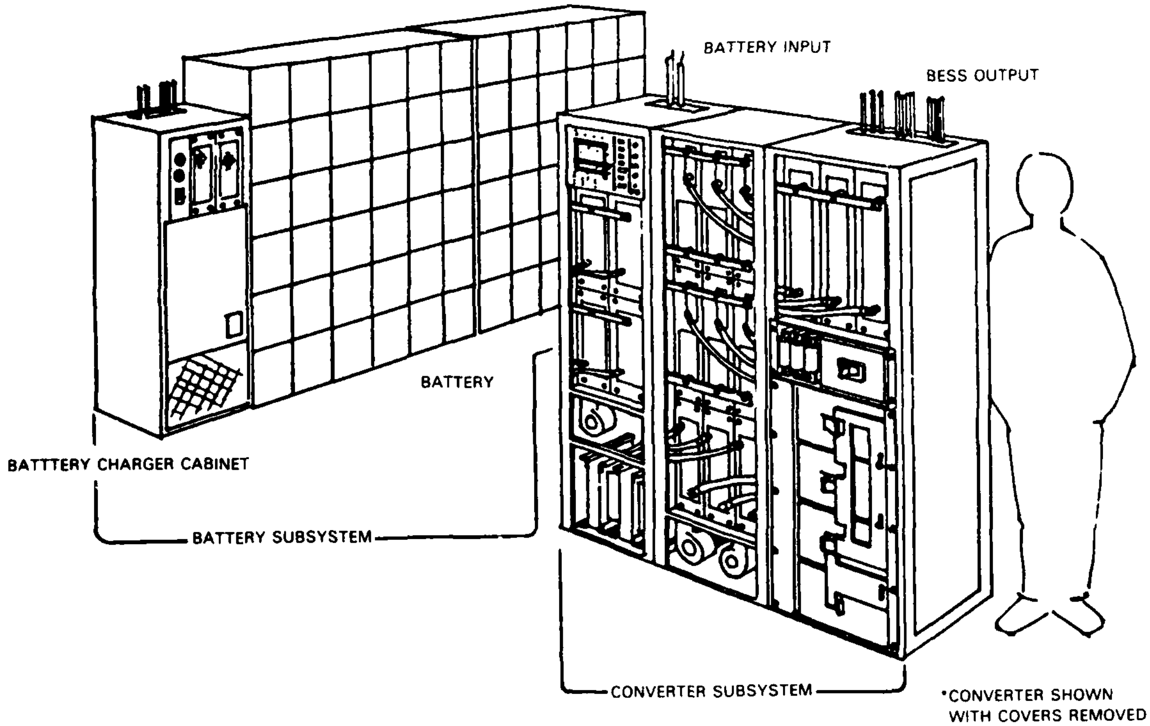


Fig. 35. 250 kVA battery energy storage system.

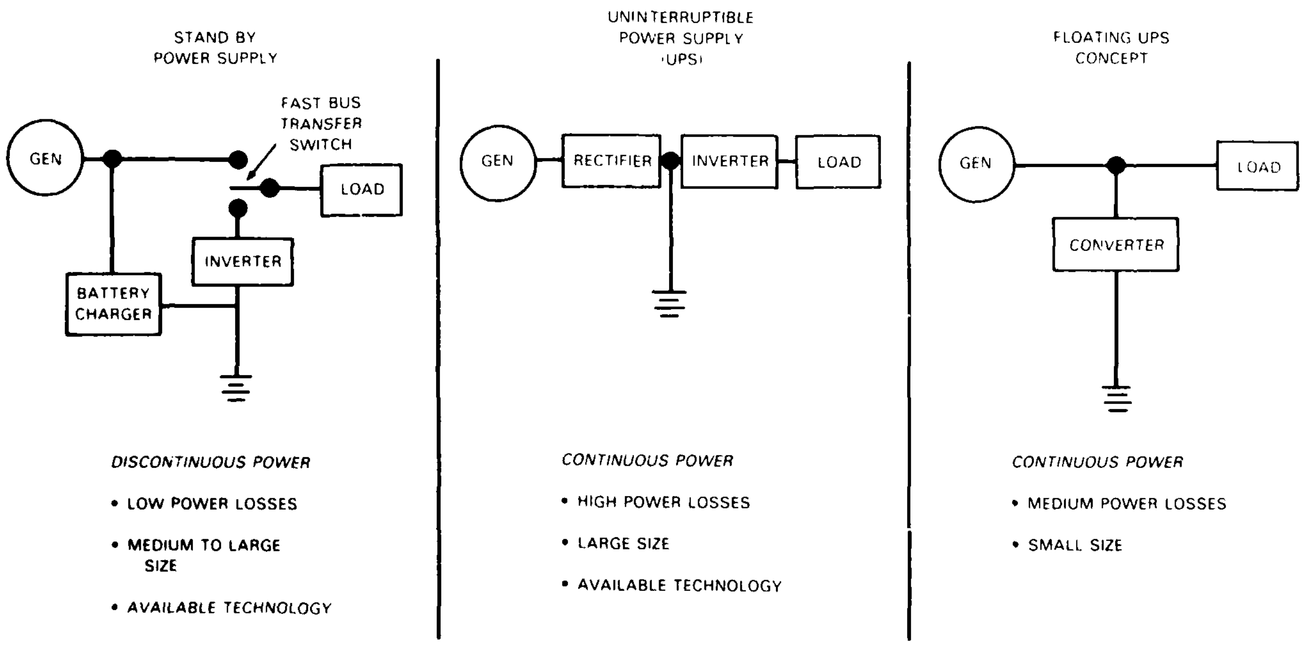


Fig. 36. Ship service battery backup system.

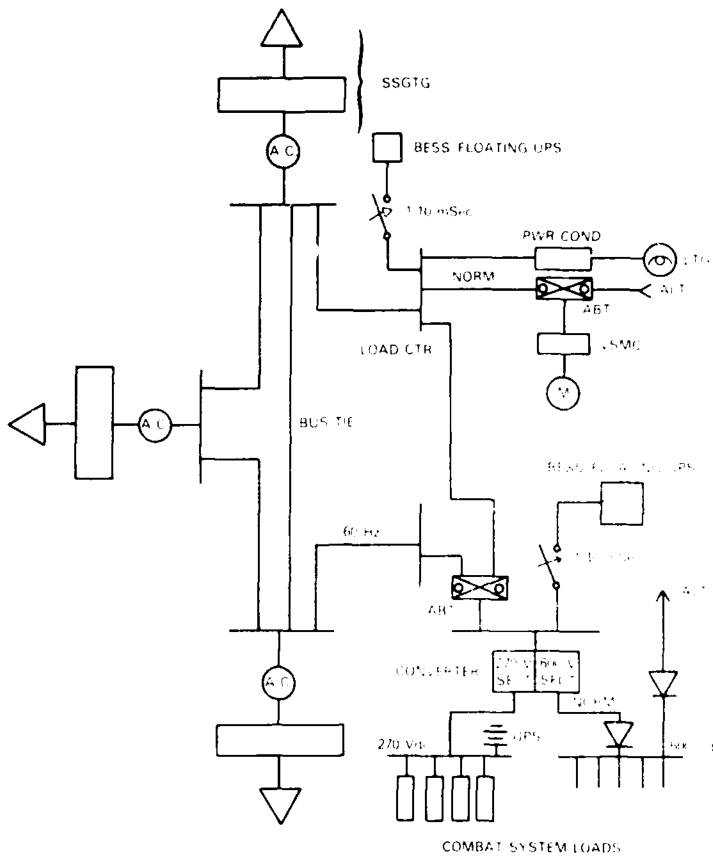


Fig. 37. 60 Hz ship service system with dc for vital loads.

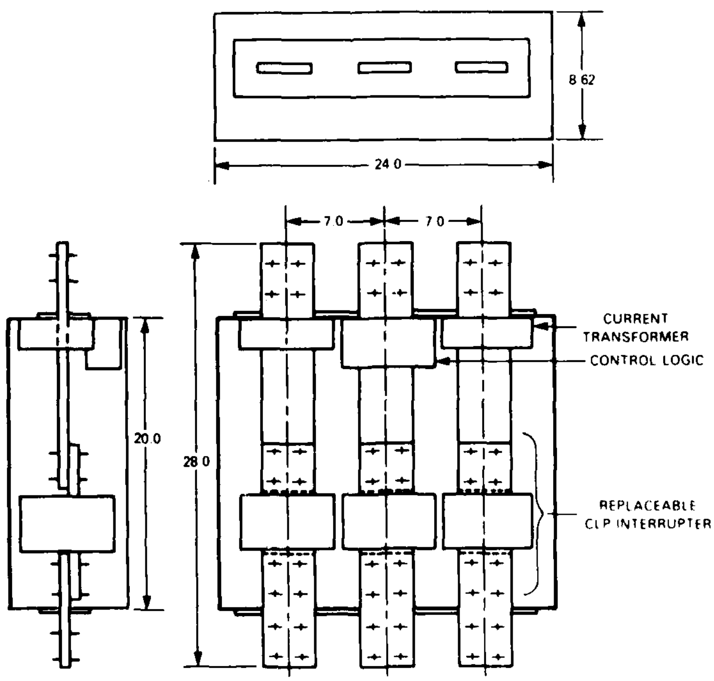


Fig. 38. Current limiter with replaceable pyrotechnic elements.

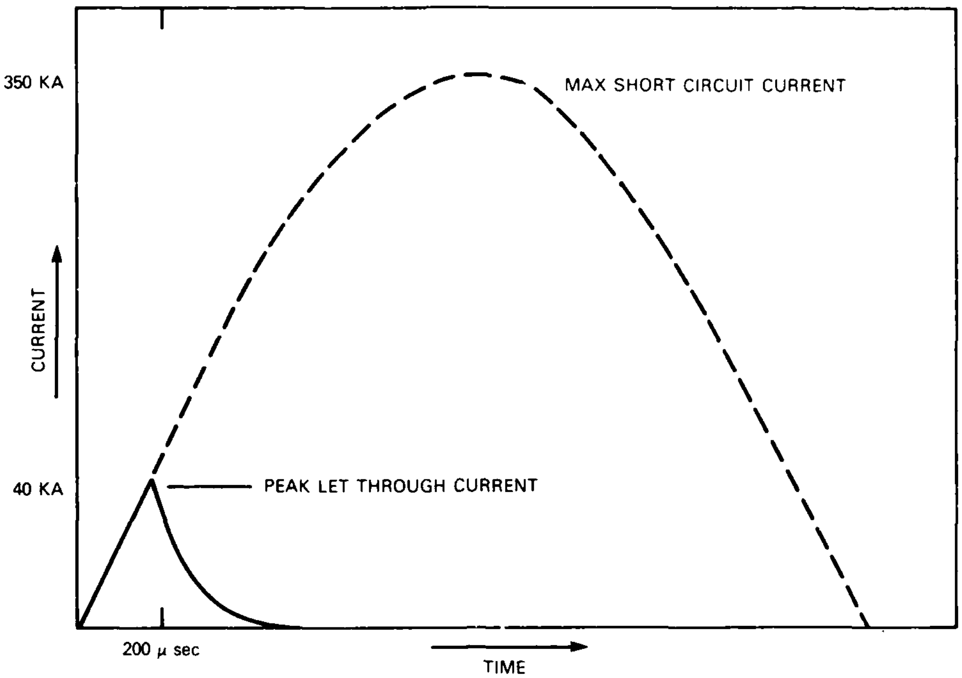


Fig. 39. Current limiter performance.

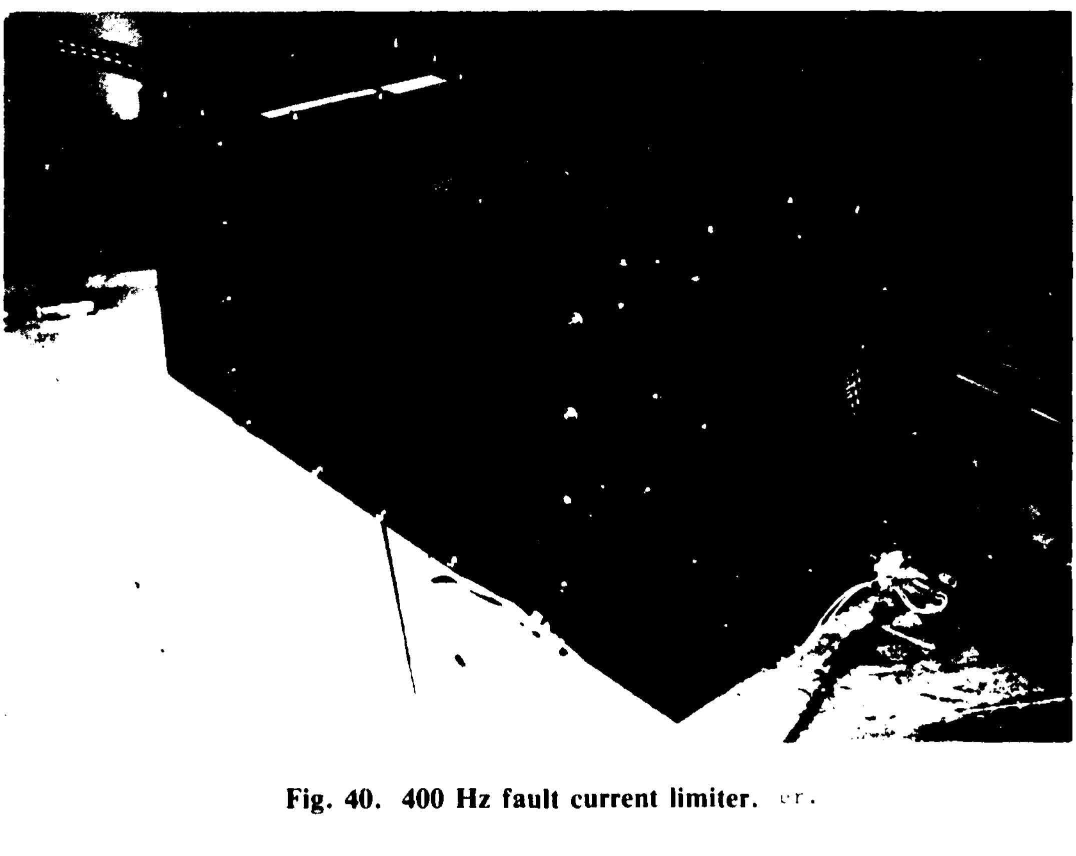


Fig. 40. 400 Hz fault current limiter.

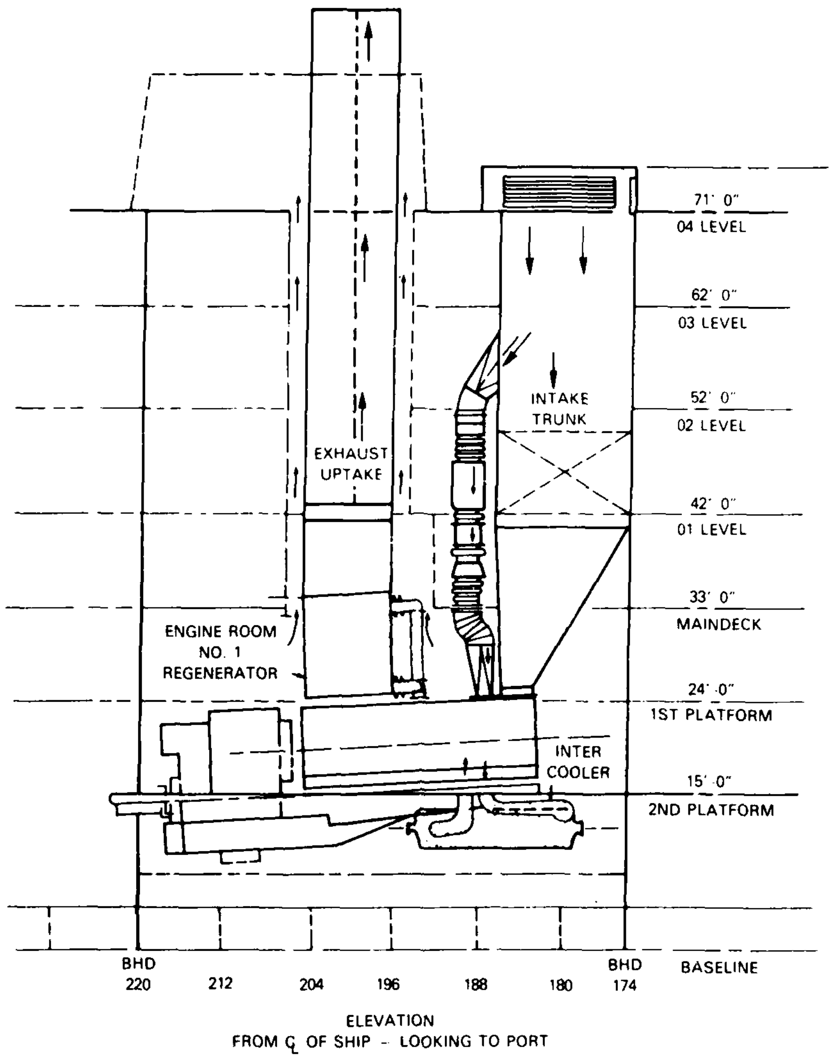


Fig. 41. Propulsion machinery.

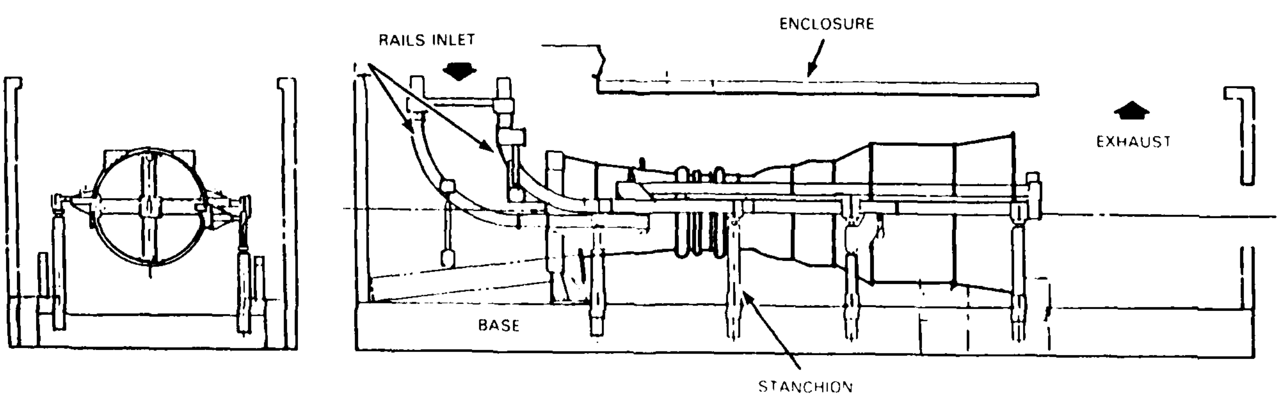


Fig. 42. Main propulsion gas turbine replacement system.

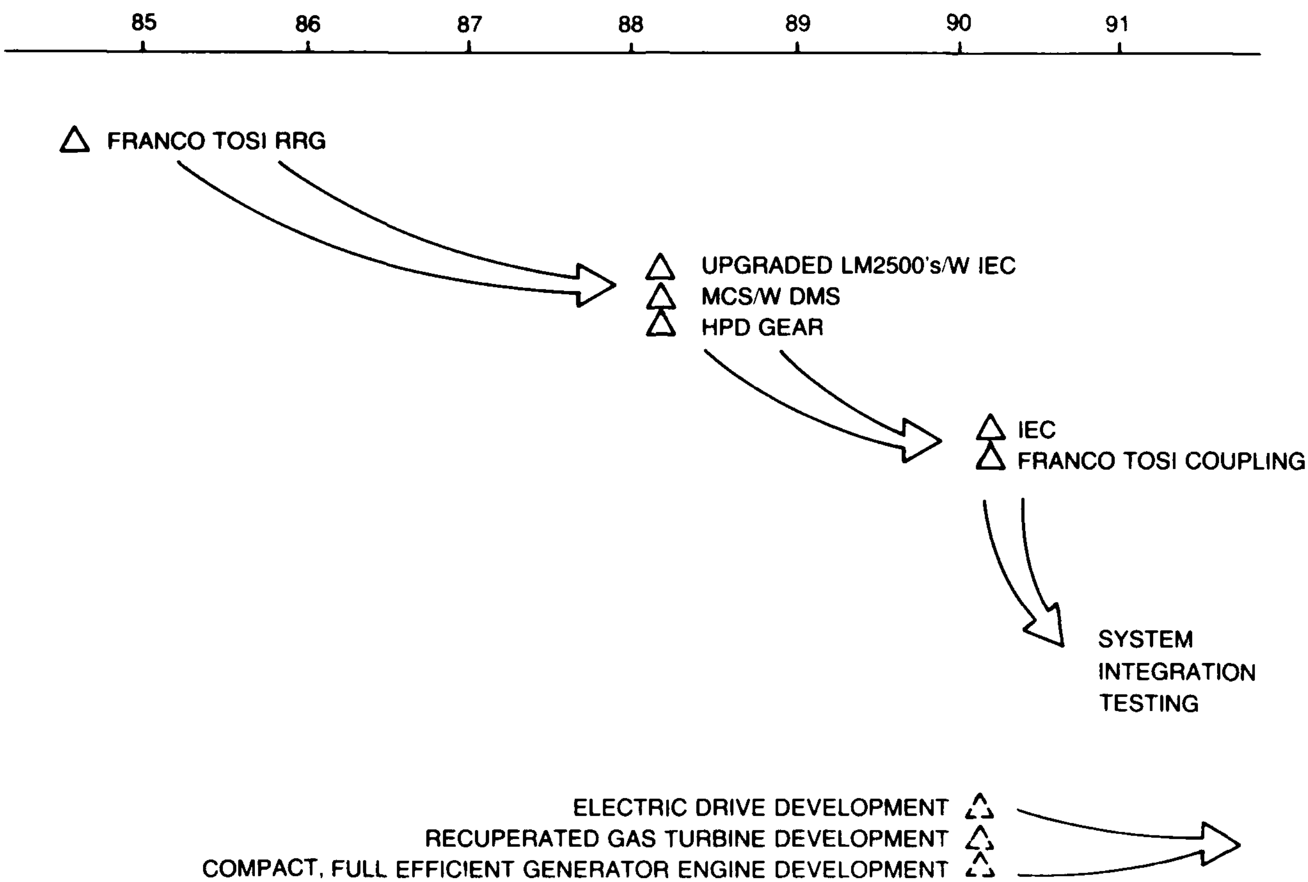


Fig. 43. Propulsion machinery development.

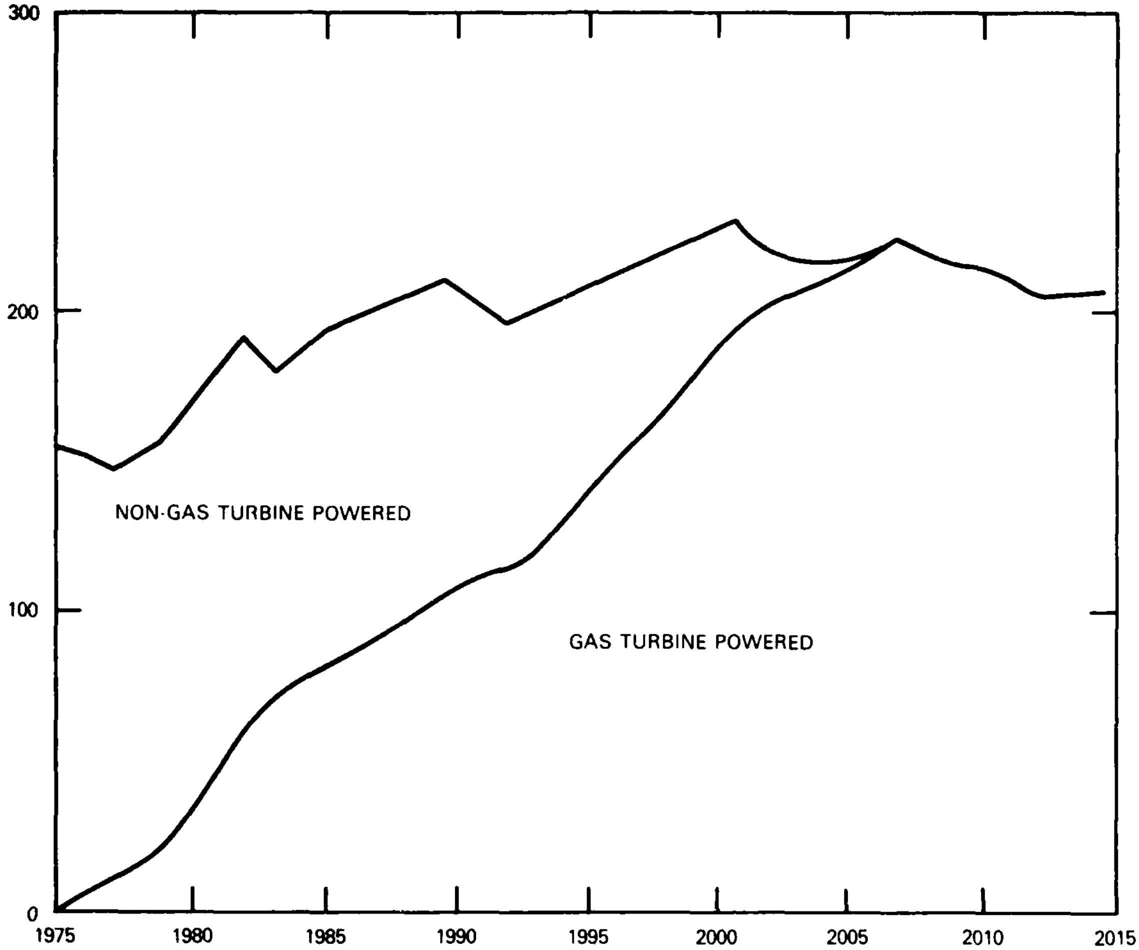


Fig. 44. Projected combatant gas turbine utilization.

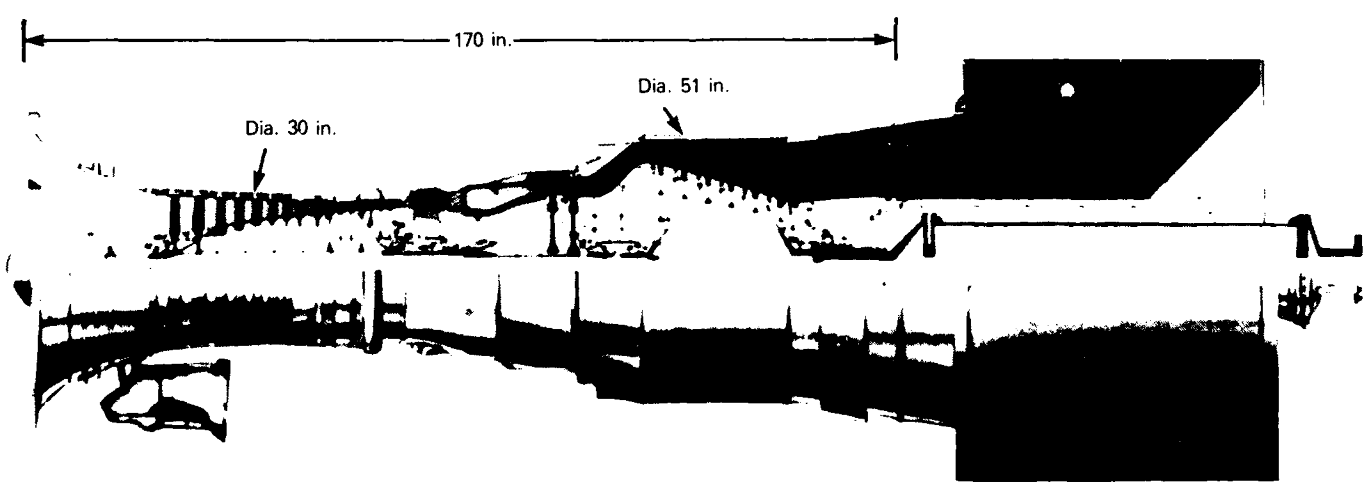


Fig. 45. U.S. Navy main propulsion gas turbine LM2500.

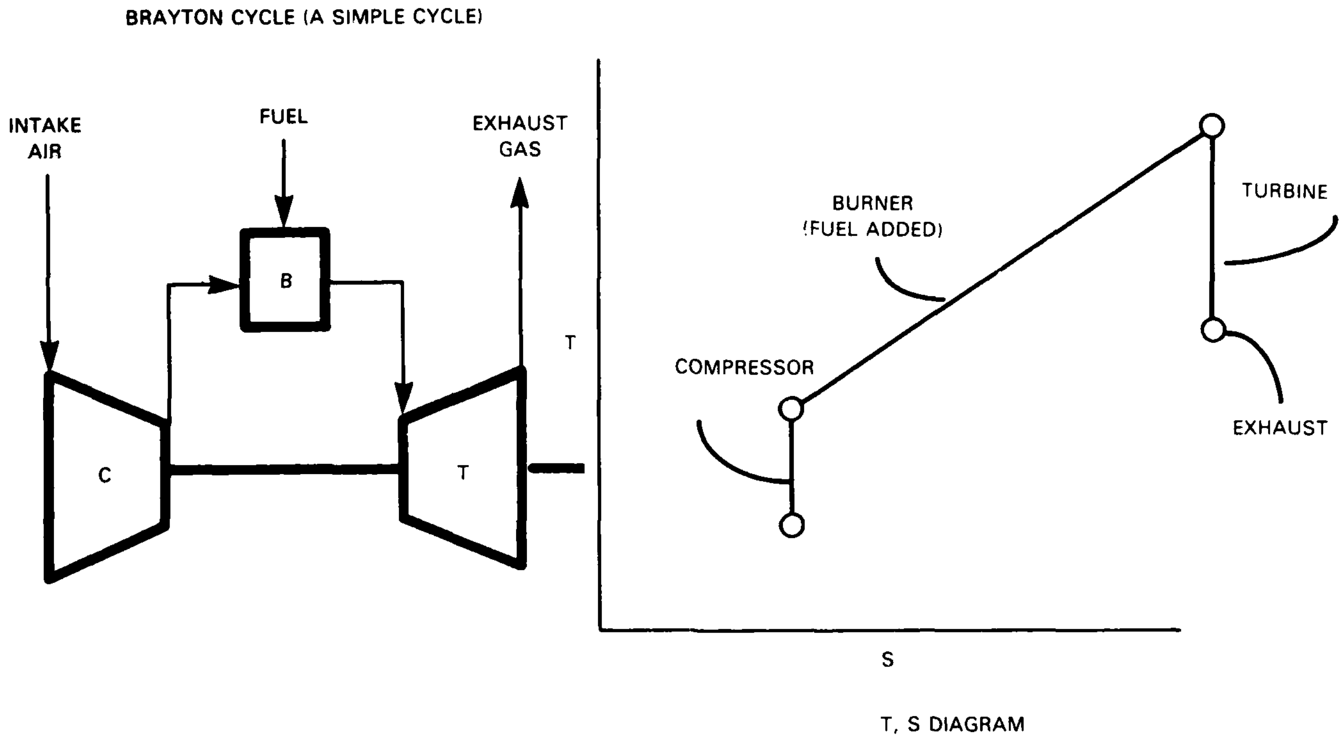


Fig. 46. Marine propulsion gas turbines.

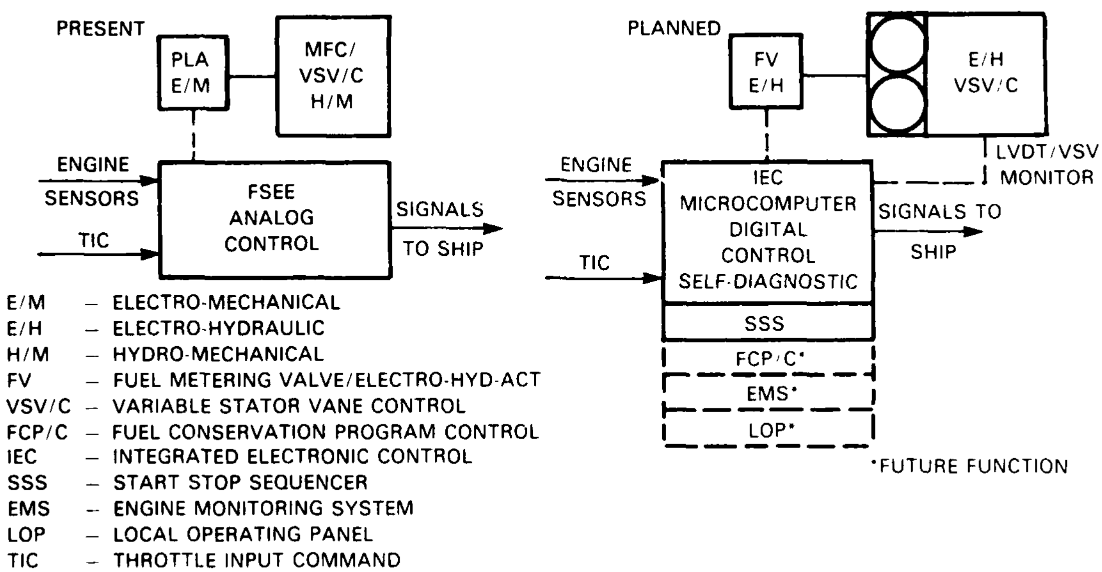


Fig. 47. LM2500 off-engine integrated electronic control system (IEC).

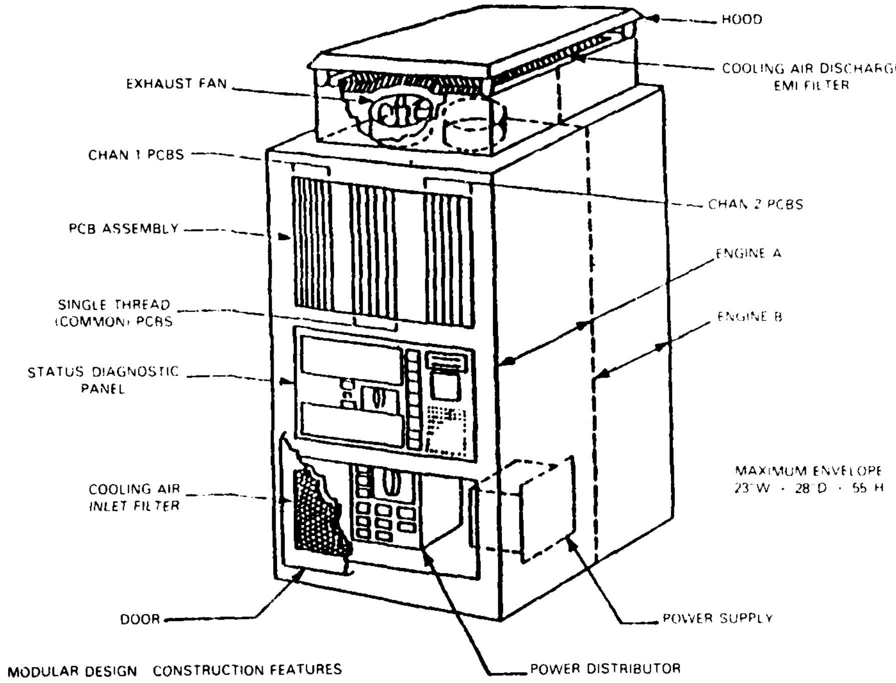


Fig. 48. LM2500 IEC single cabinet-dual engine arrangement.

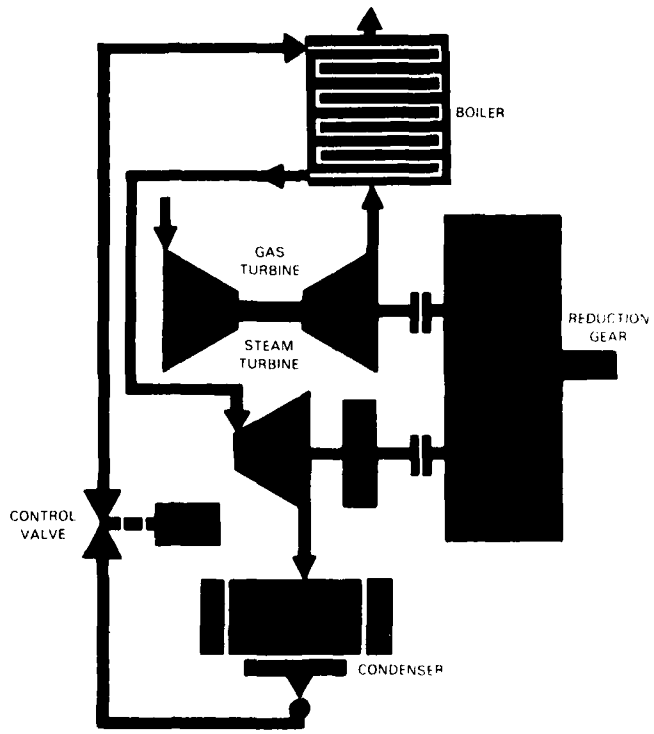


Fig. 49. Rankine cycle energy recovery (RACER).

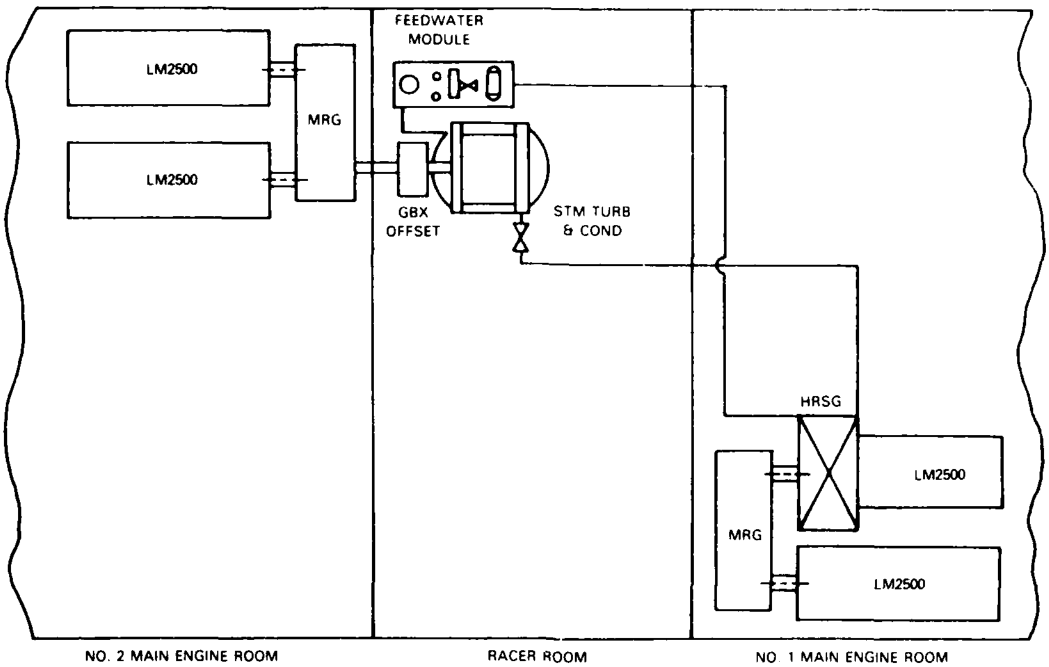


Fig. 50. RACER system shipboard arrangement.

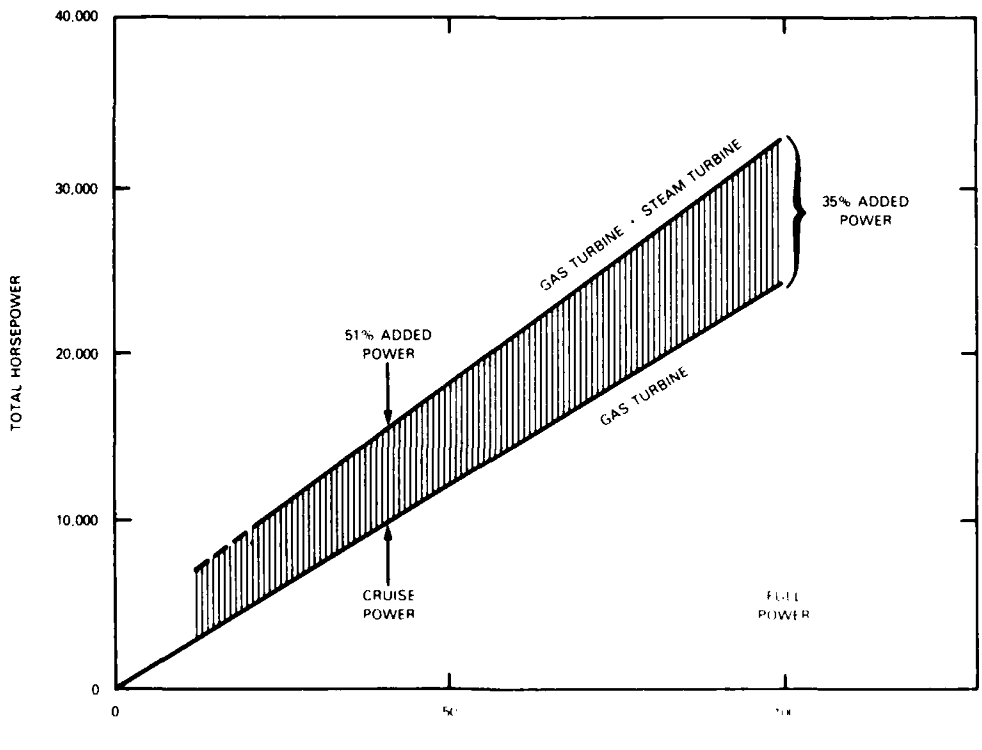
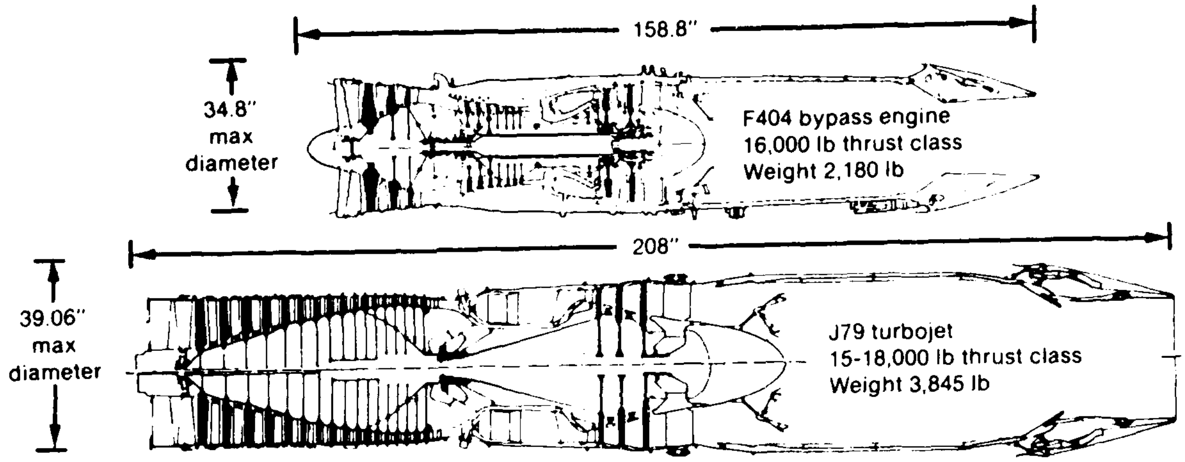


Fig. 51. RACER combined cycle power split.



The F404 has
- The same thrust
- 1/2 the weight
- 3/4 the length
- 11% smaller diameter
- 650° F cooler skin at turbine casing
- No need for secondary airflow system
- twice the pressure ratio
- 14% less airflow
- 8 fewer turbomachinery stages
- 1/3 less parts
- Annular versus cannular (10) combustor

Fig. 52. Gas turbine technology comparison.

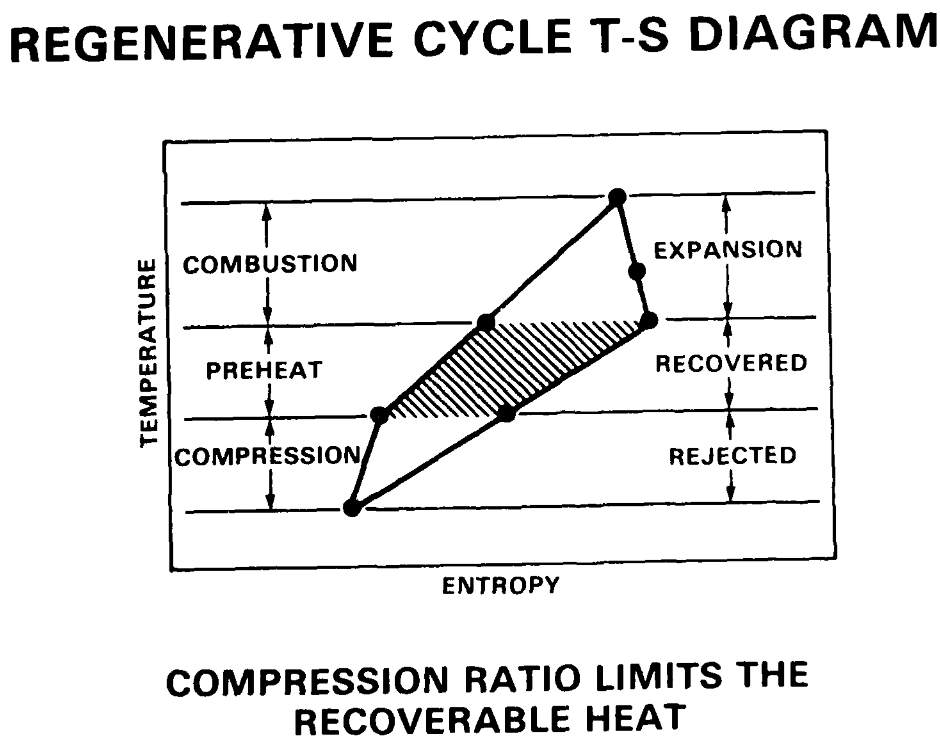


Fig. 53. Heat recovery potential.

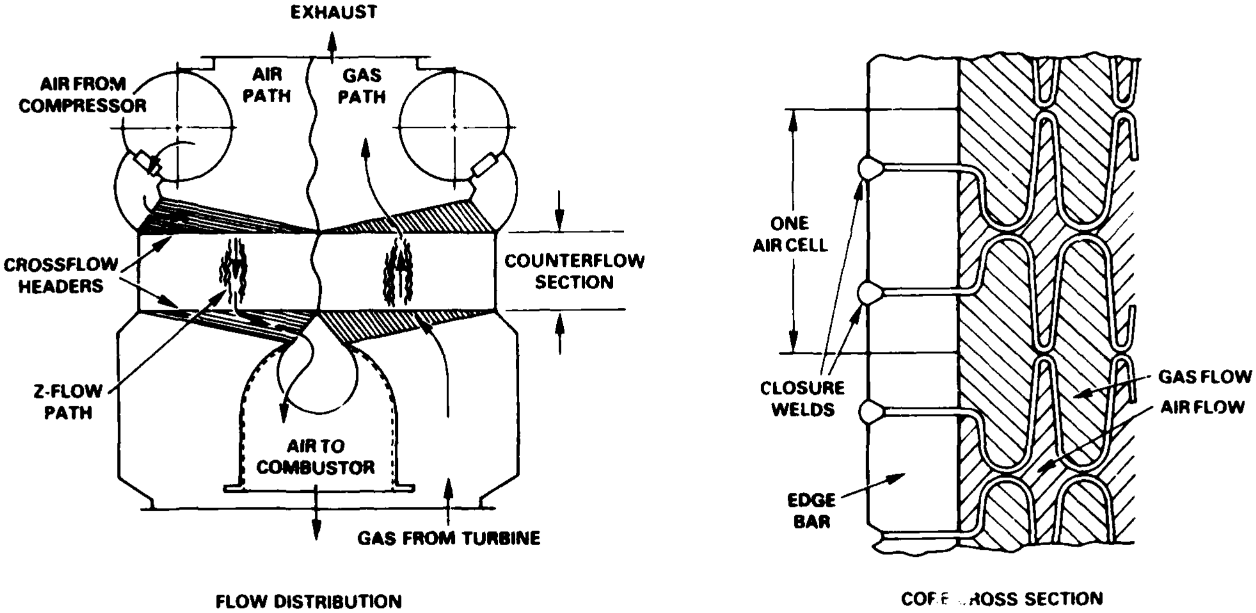


Fig. 54. Primary surface recuperator design features.

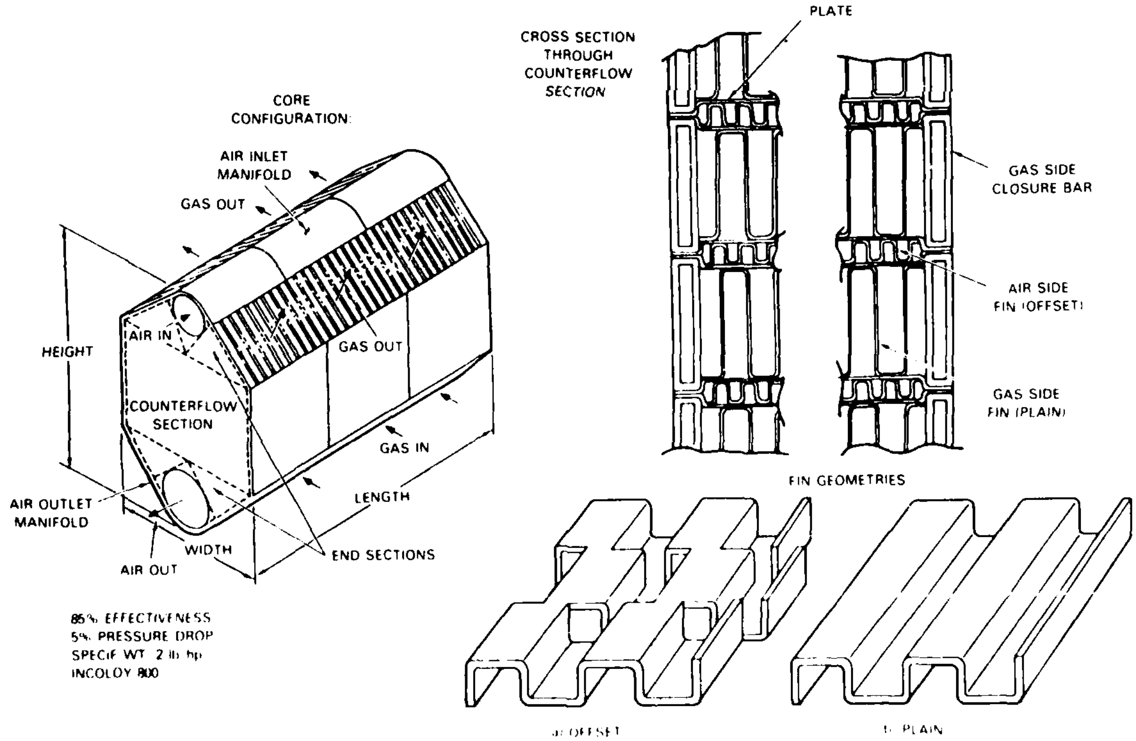


Fig. 55. Plate fin recuperator design features.

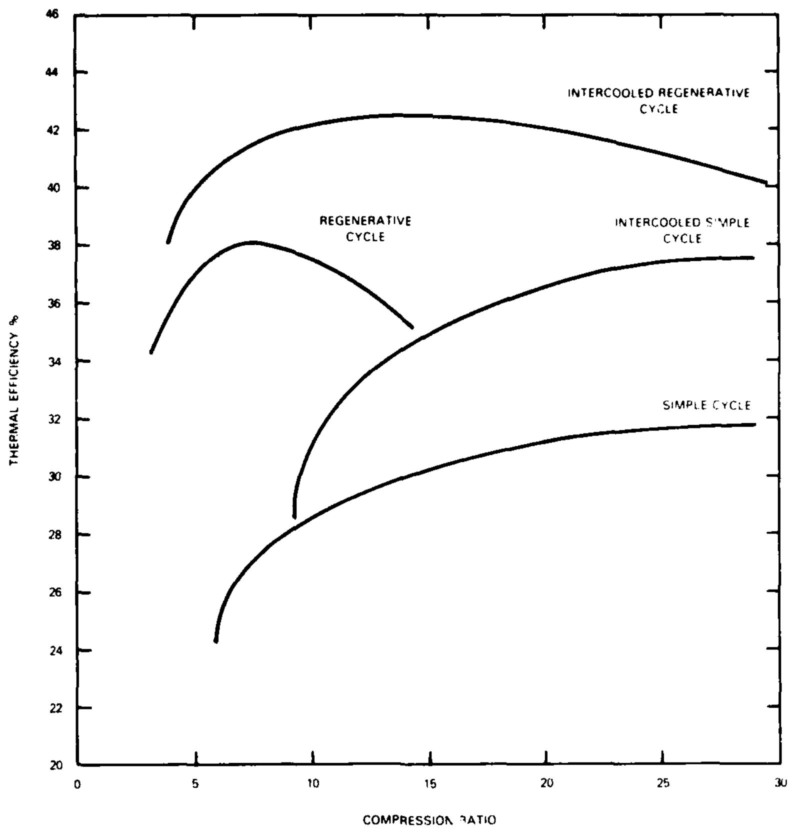


Fig. 56. Marine gas turbine thermal efficiency vs. compression ratio.

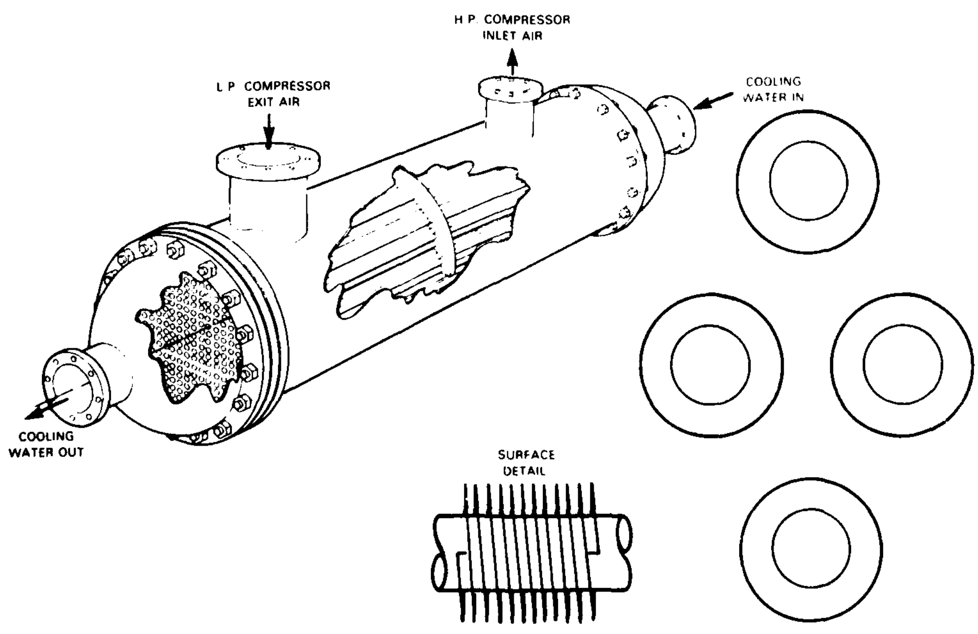


Fig. 57. Intercooler.

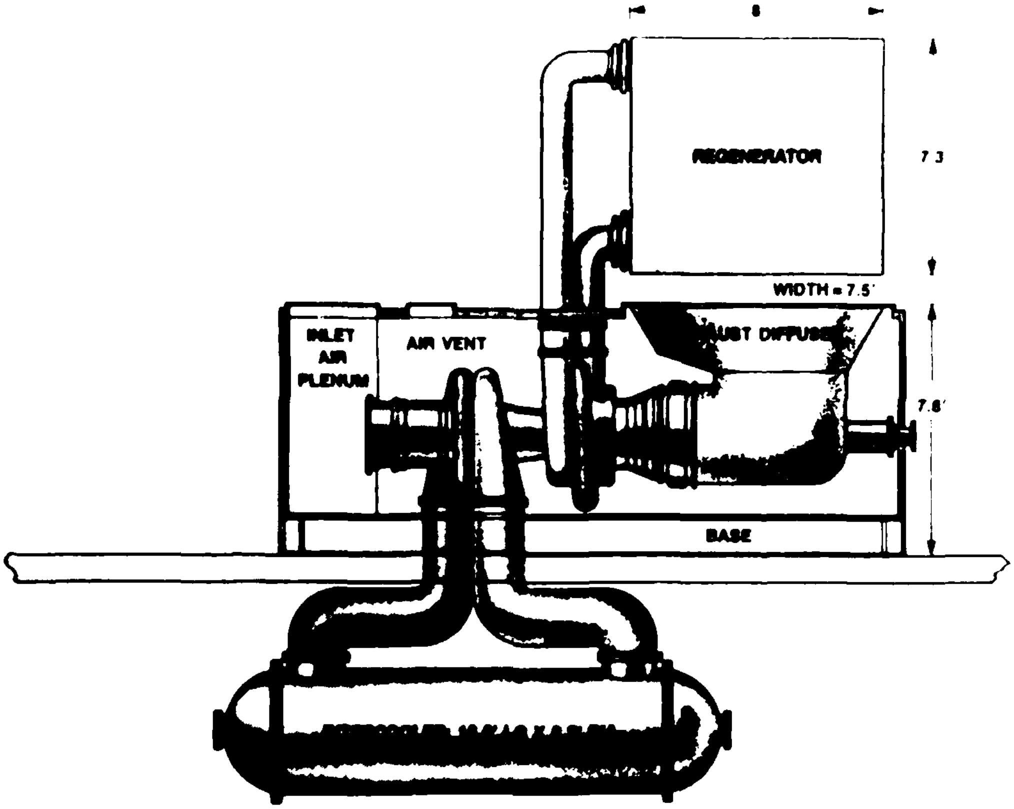


Fig. 58. ICR engine schematic diagram (not to scale).

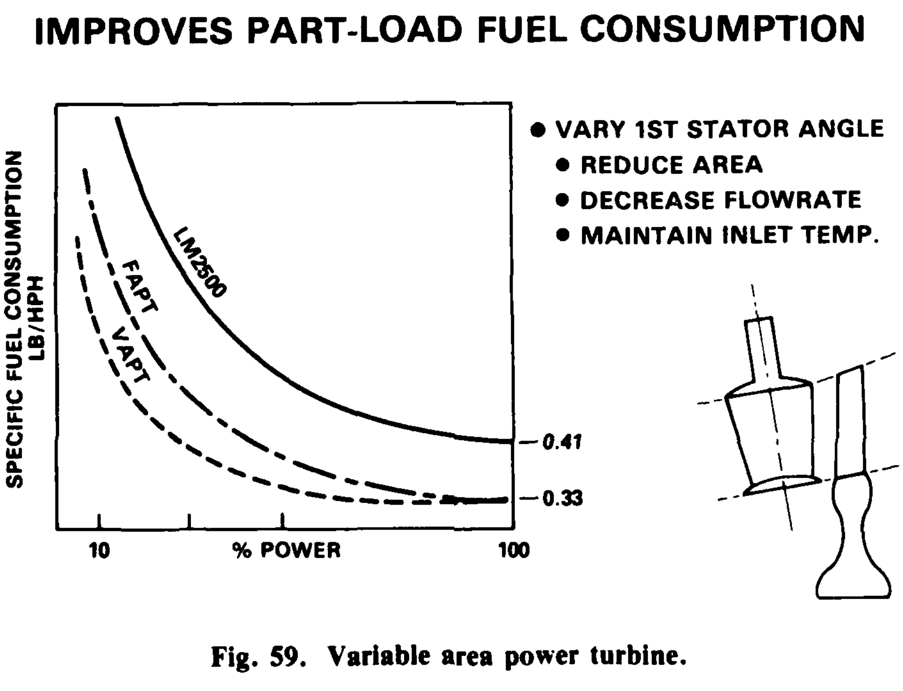


Fig. 59. Variable area power turbine.

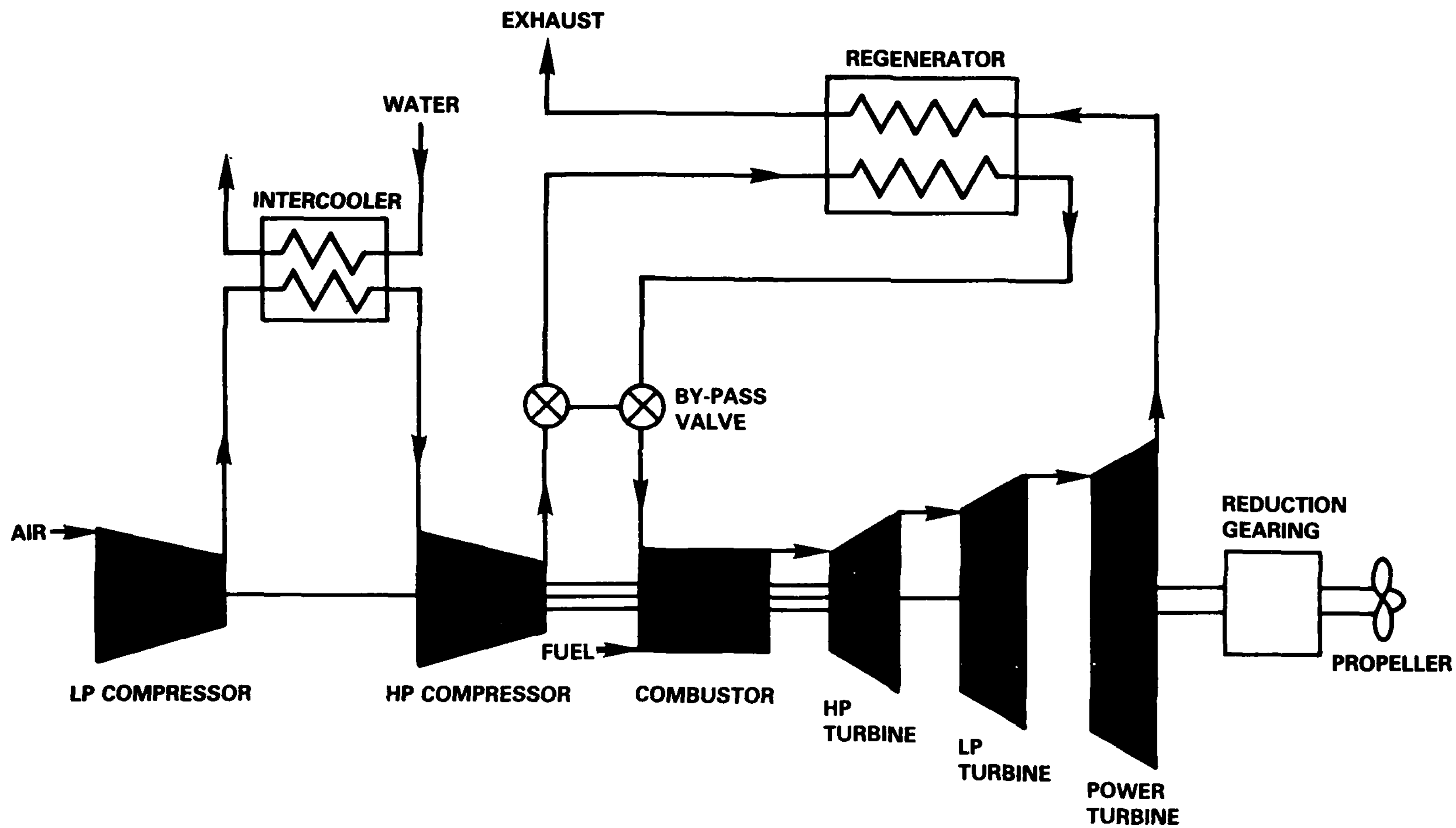


Fig. 60. Intercooled/recuperated gas turbine.

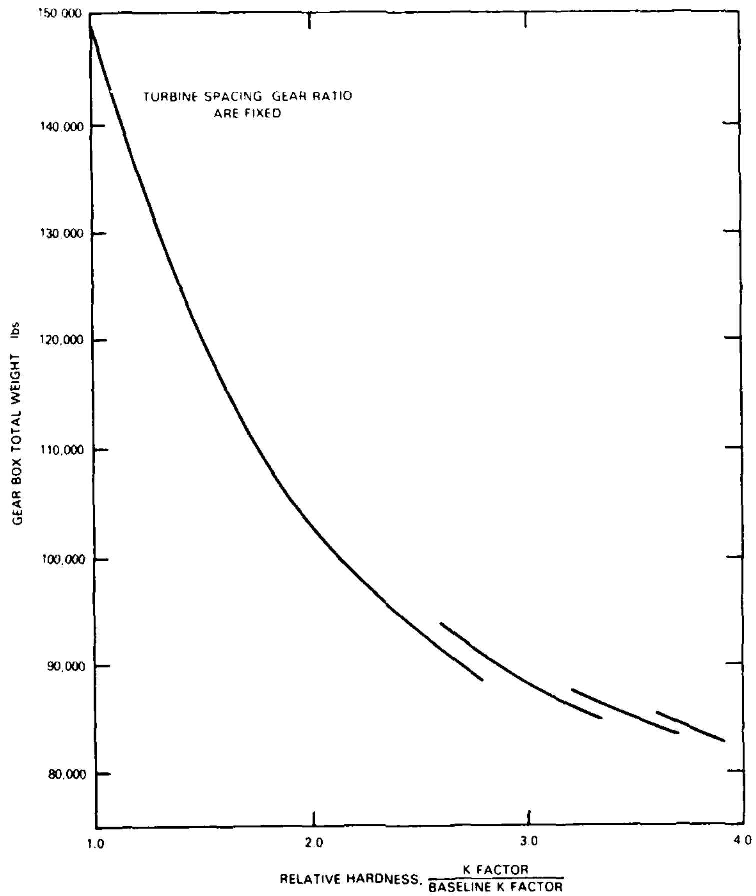


Fig. 61. Main reduction gear weight vs. K factor.

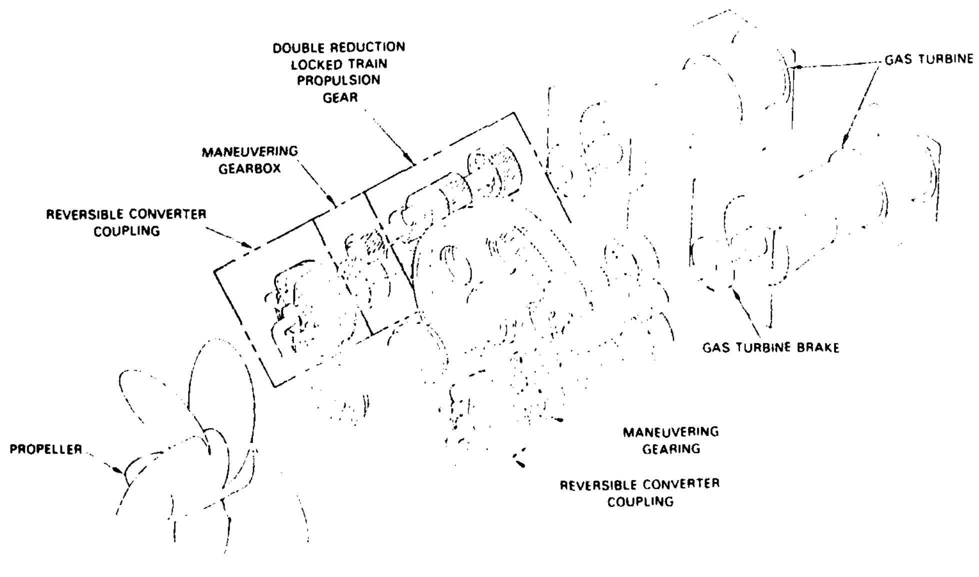


Fig. 62. Main reduction gear arrangement.

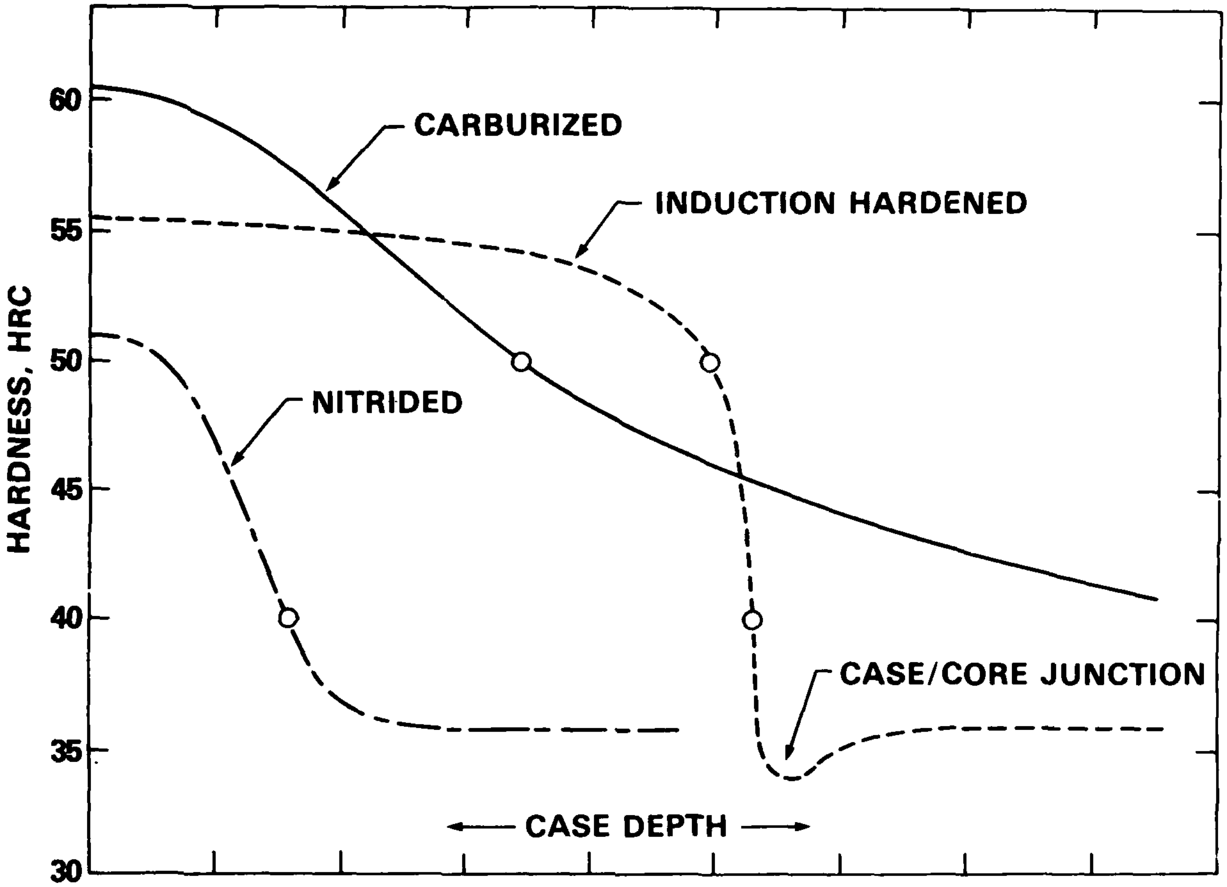


Fig. 63. Comparison of three methods of case hardening.

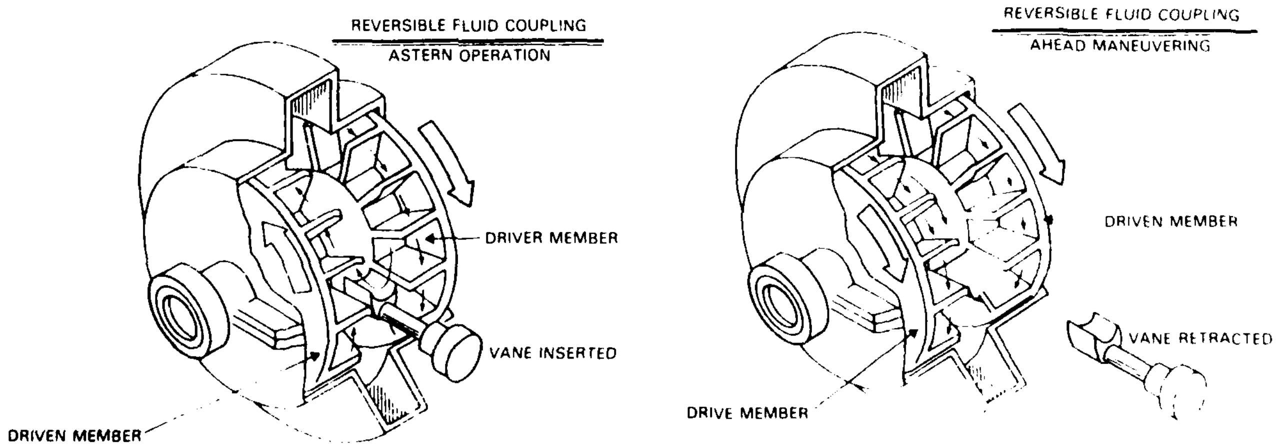


Fig. 64. Main propulsion reverse reduction gear (RRG), Franco-Tosi design.

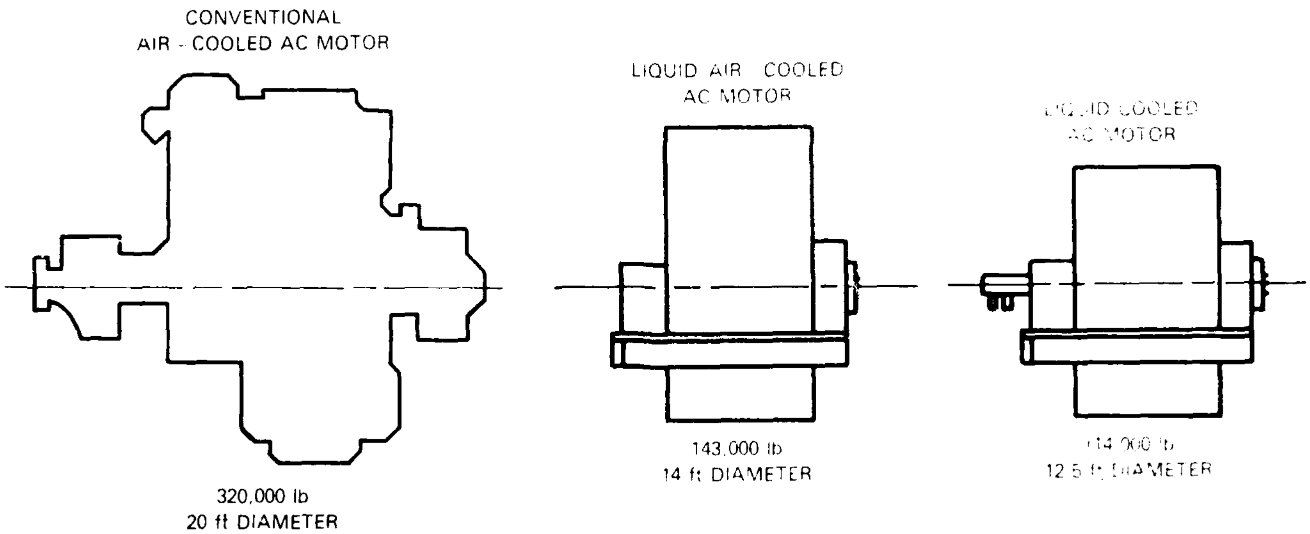


Fig. 65. Impact of liquid cooling on a 40,000 hp, 180 rpm motor.

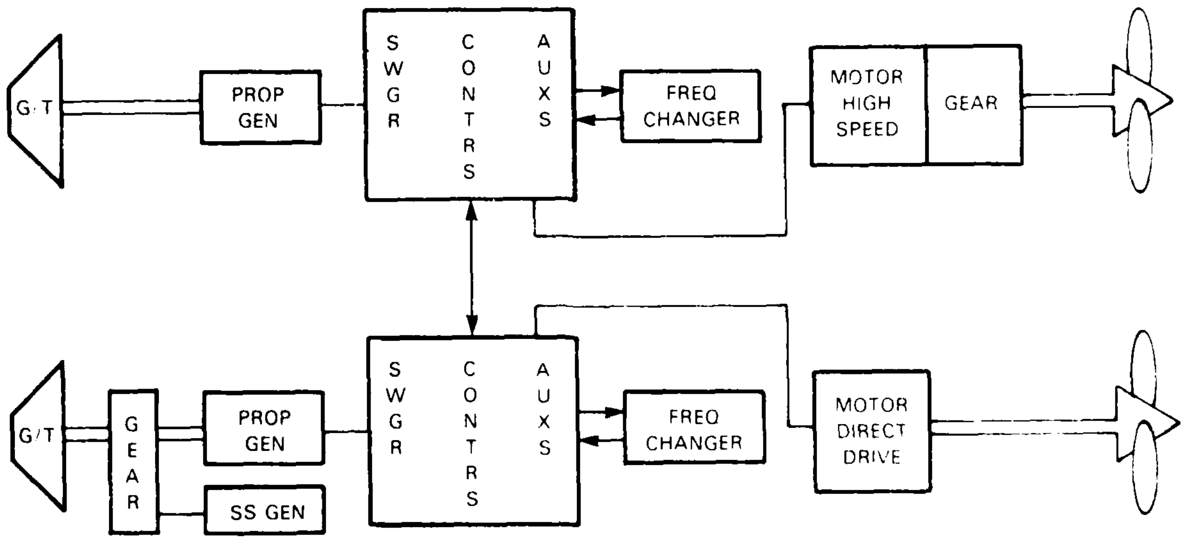


Fig. 66. Near term ac drive system candidates.

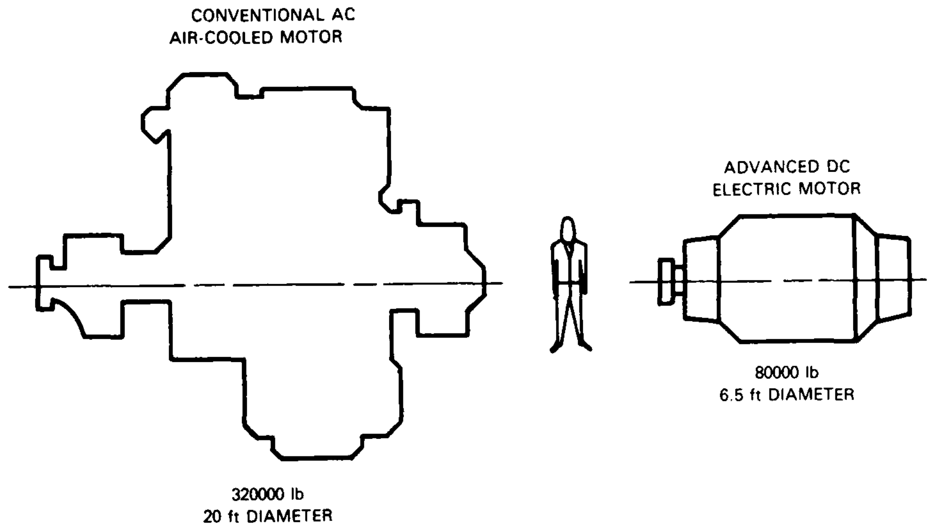


Fig. 67. Advanced dc versus conventional ac 40,000 hp, 180 rpm motors.

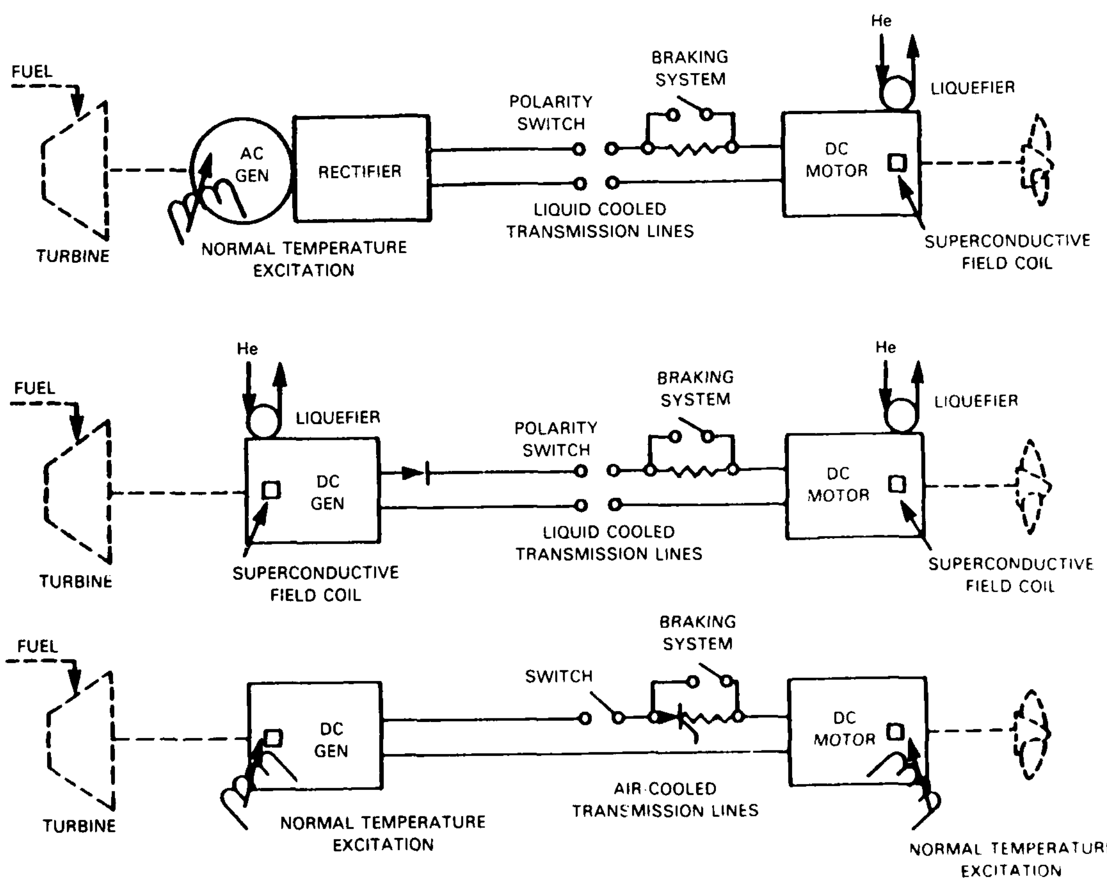


Fig. 68. Direct current drive system options.

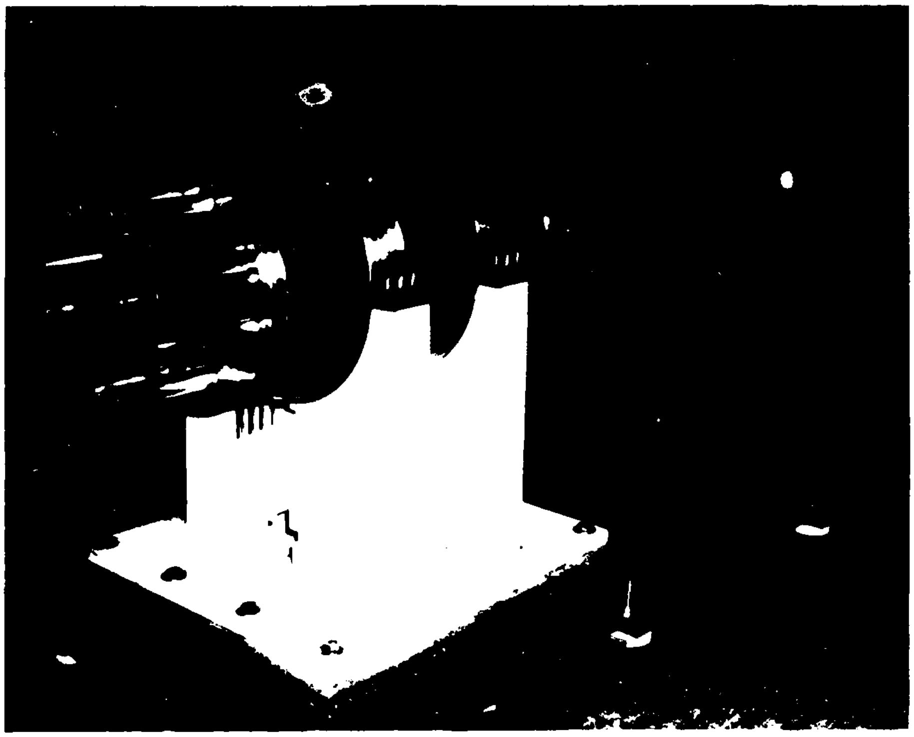


Fig. 69. 300 kW acyclic dc machinery.

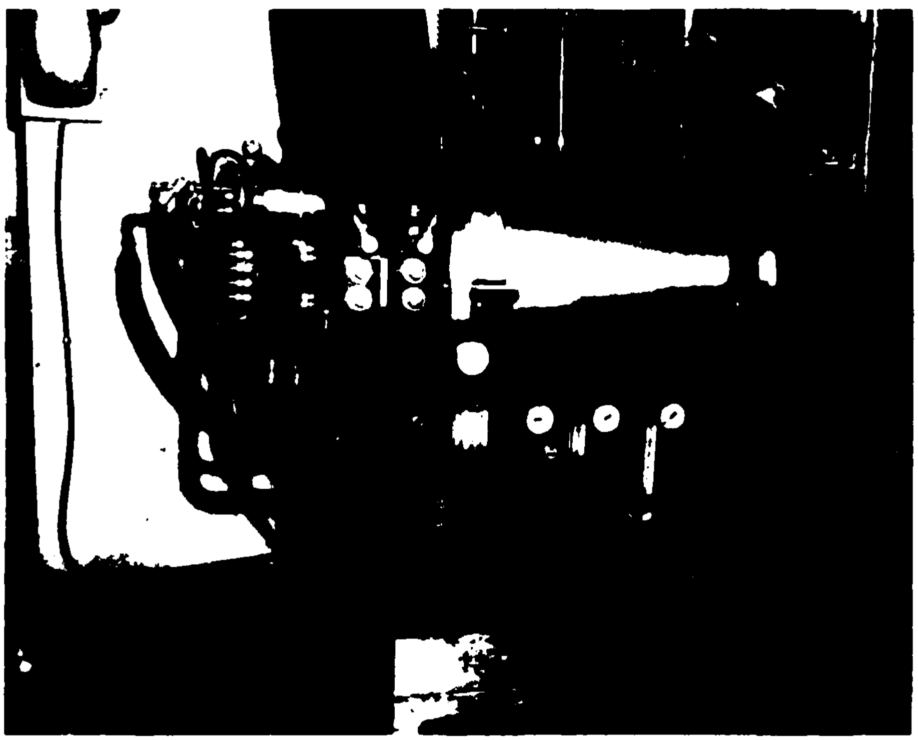


Fig. 70. 300 kW acyclic dc machinery.

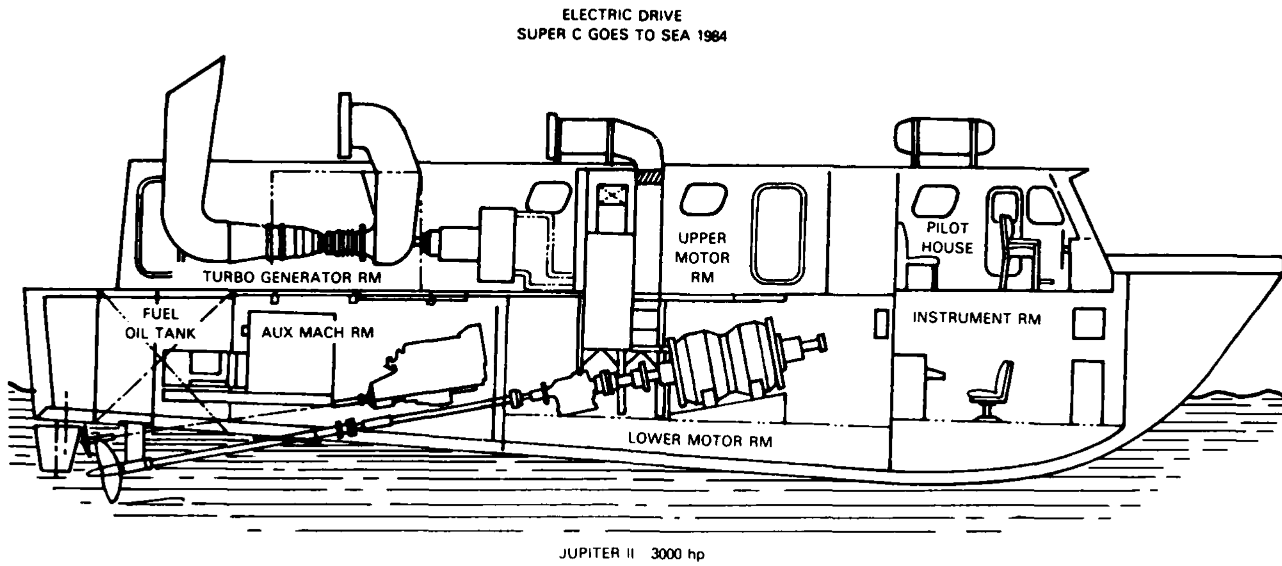


Fig. 71. JUPITER II-3000 hp.

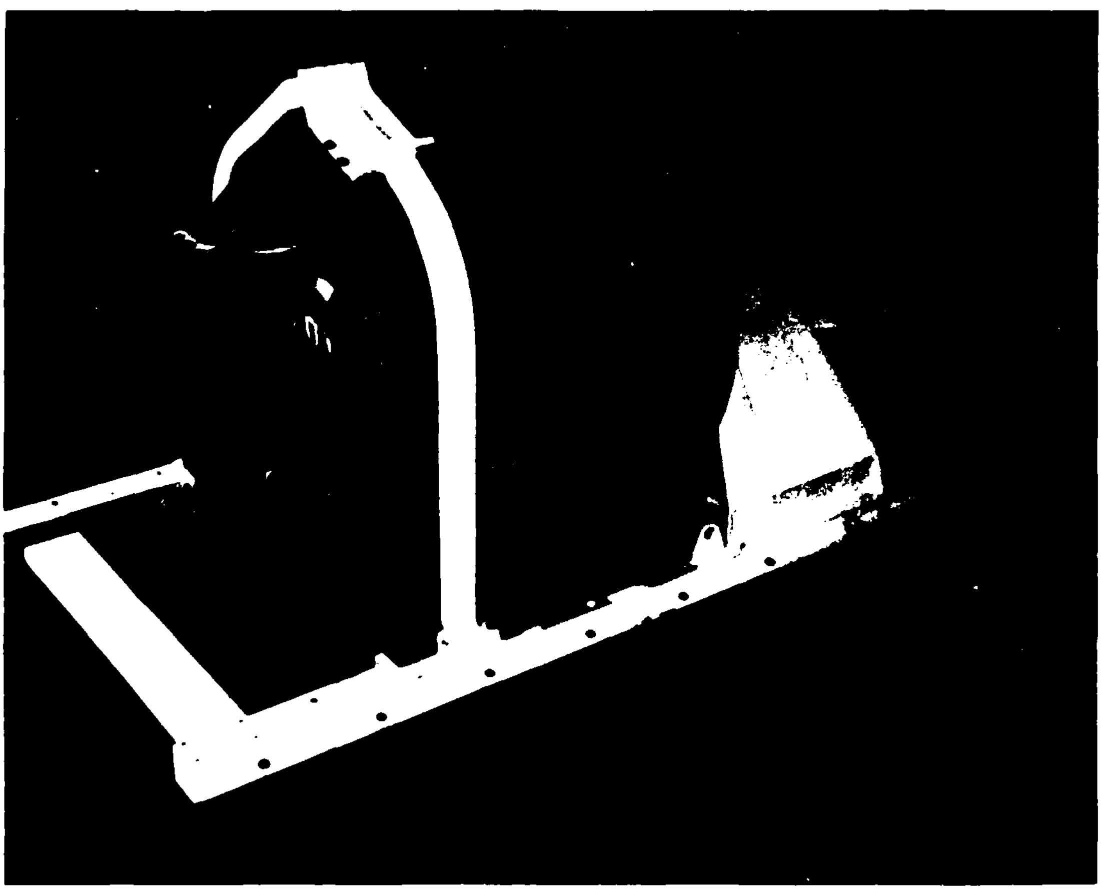


Fig. 72. Rectified alternator.

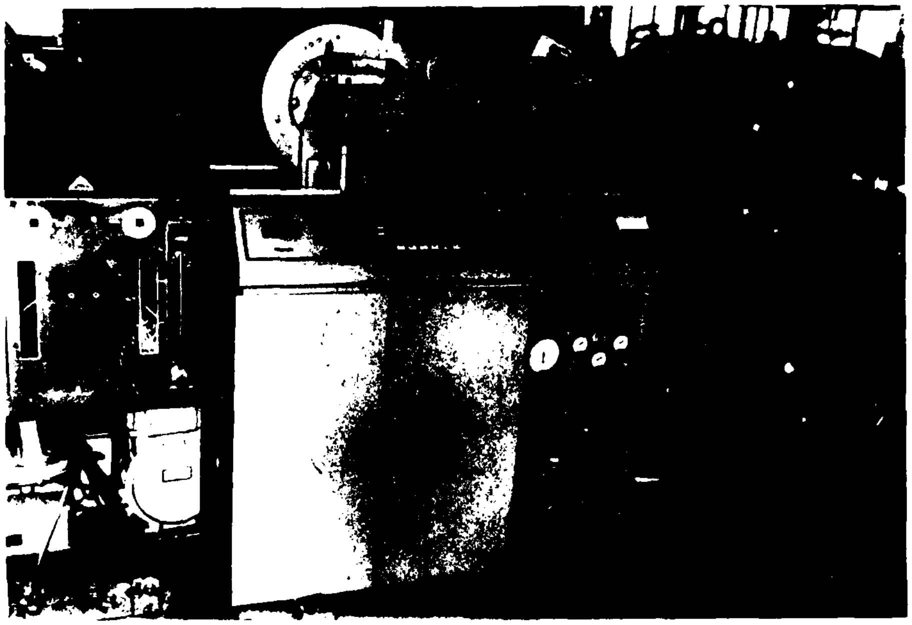


Fig. 73. 10 L/hr closed cycle helium refrigerator.

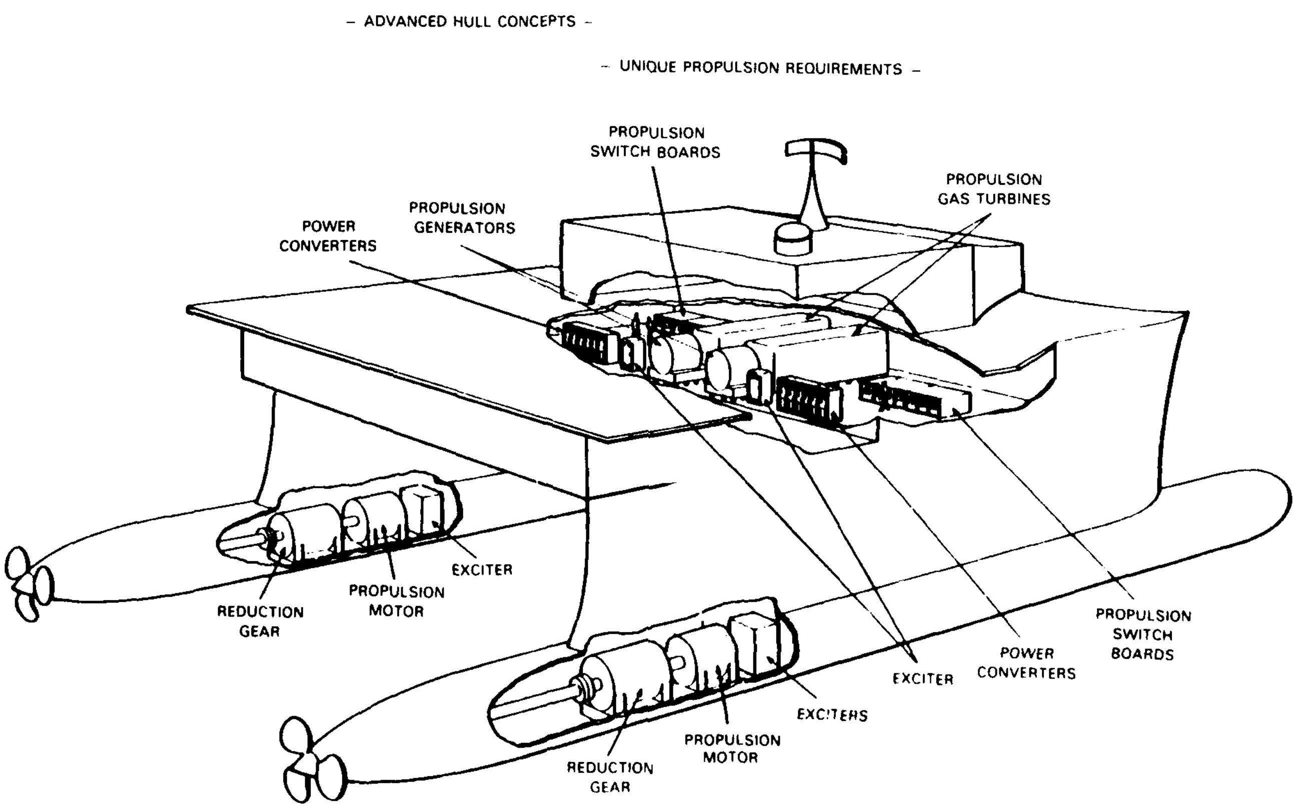


Fig. 74. Advanced hull concepts.

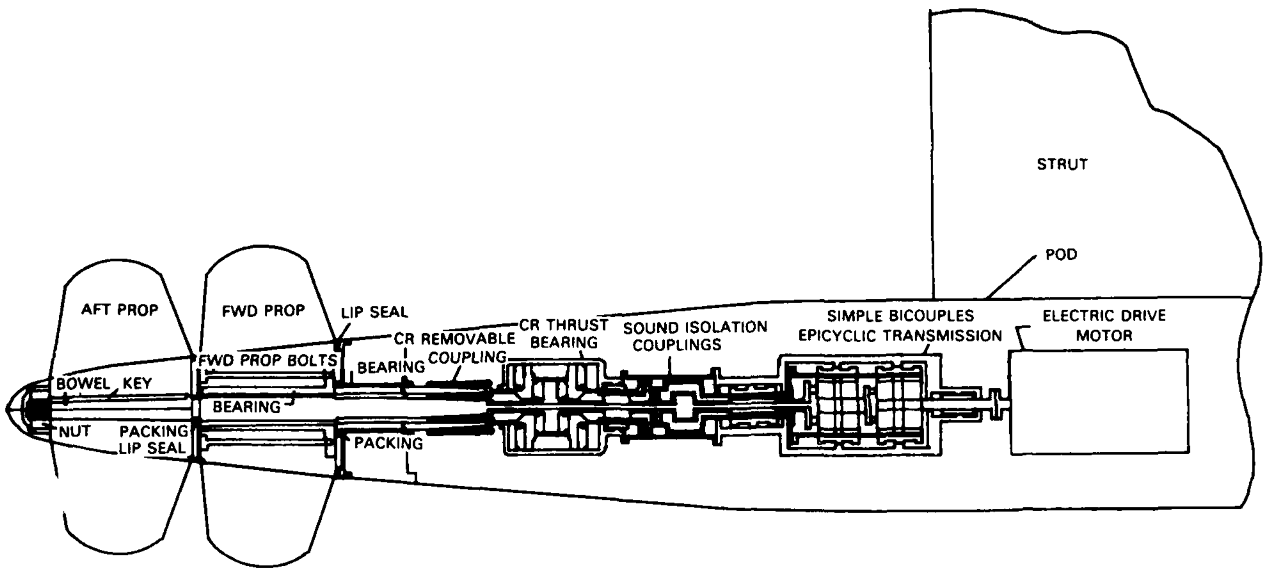


Fig. 75. Conceptual contrarotating propulsion machinery arrangement.

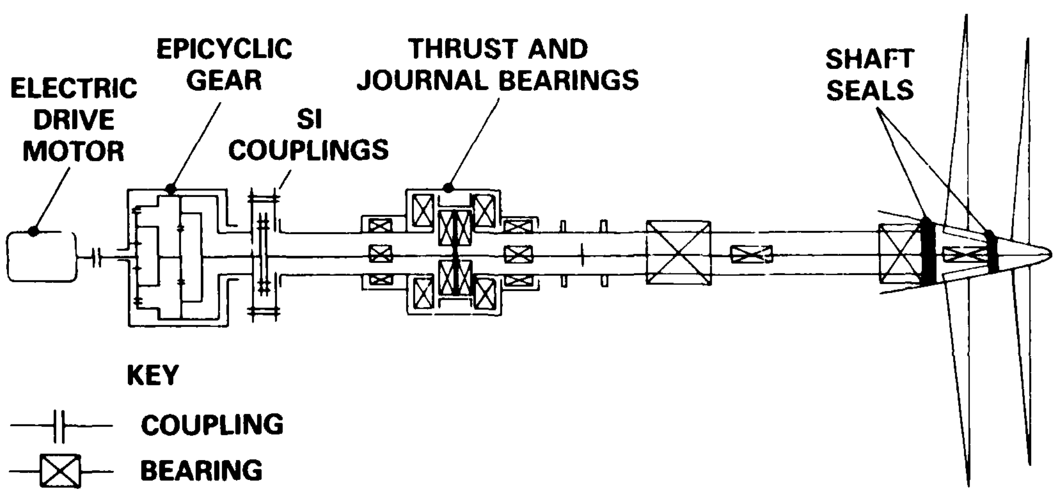


Fig. 76. Contrarotating shaftline arrangement.

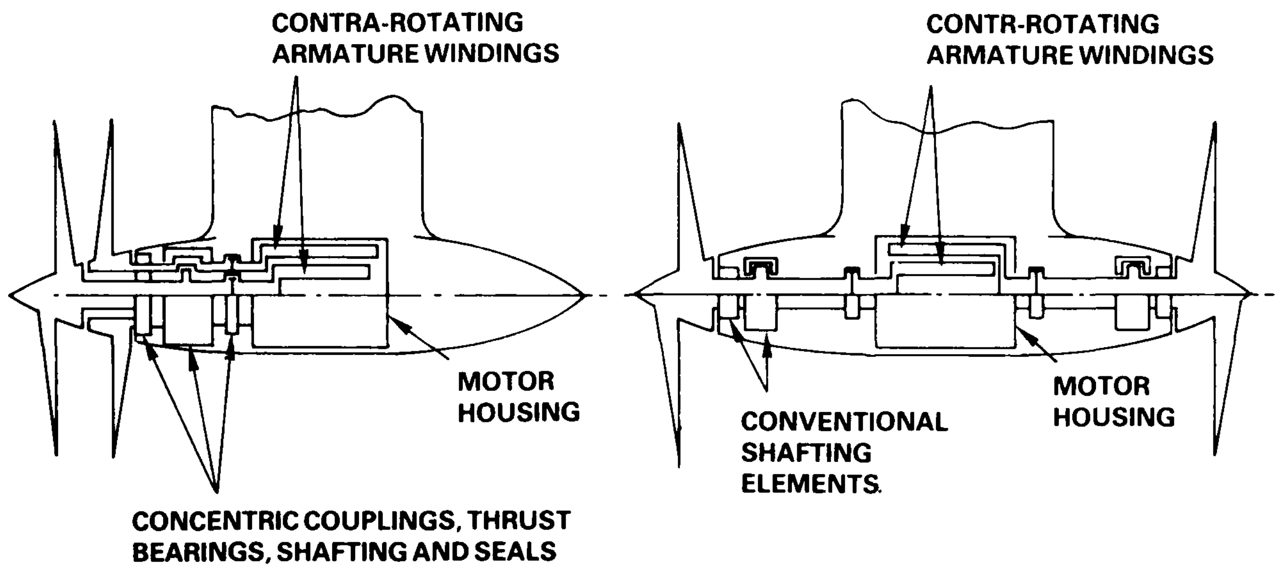


Fig. 77. Contrarotating shaftline arrangement.

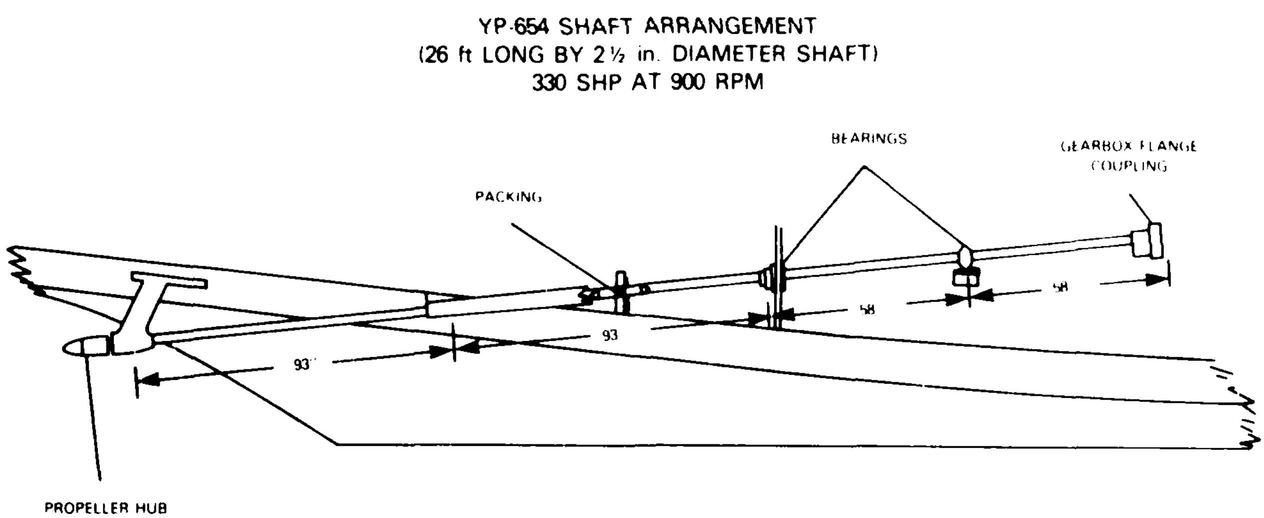


Fig. 78. Main propulsion composite shafting.

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